Guide to **Tremie Concrete** for Deep Foundations

By the joint **EFFC/DFI** Concrete Task Group

EUROPEAN FEDERATION OF FOUNDATION CONTRACTORS

DEEP FOUNDATIONS INSTITUTE

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The contents of this Guide reflect the views of the authors, who are responsible for the facts and accuracy of the data presented herein. This Guide does not constitute a standard, specification or regulation.

TERMINOLOGY	DEFINITION
addition (filler and SCM: supplementary cementitious material)	Finely divided inorganic material used in concrete to improve certain properties or achieve special properties. These comprise two main types:- Type I) - inert and nearly inert (filler) e.g. limestone powder Type II) - latent hydraulic or pozzolanic (SCM) e.g. fly ash or ground-granulated blast furnace slag.
admixture	Consituent added during the concrete mixing process in small quantities related to the mass of cement to modify the properties of fresh or hardened concrete. Admixtures are also known as chemical admixtures.
anomaly	A result (jn this context normally from test data) that deviates from that which is expected.
barrette (LBE: load bearing element)	A barrette is a structural cast-in place diaphragm wall element, (with or without reinforcement), normally of I, H, L or T cross section in plan. Also referred to as a deep foundation. See Figure 1.
bentonite	Clay containing the mineral montmorillonite, used in support fluids, either as pure bentonite suspension or as an addition to polymer solutions. Also used as a constituent in non-structural concrete.
binder (cementitious)	Inorganic material or a mixture of inorganic materials which, when mixed with water, form a paste that sets and hardens by means of hydration reactions and processes which, after hardening, retains its strength and stability even under water.
Bingham fluid model	A two parameter rheological model of a fluid with non-zero yield stress and a constant plastic viscosity.
bleeding	Form of segregation in which some of the water in the concrete mix tends to rise to the surface of freshly placed concrete.
bored pile (drilled shaft or caisson)	Pile formed with or without a steel casing by excavating or boring a hole in the ground and filling with concrete (with or without reinforcement). Also referred to as a deep foundation. See Figure 1.
clear spacing	Minimum space between individual reinforcement bars or bundles of bars i.e. the opening for the concrete to flow through.
concrete	Material formed by mixing binder, coarse and fine aggregate and water, with or without the incorporation of admixtures and additions, which develops its hardened properties by hydration.
conformity testing	Integral part of the production control to validate that a concrete fulfils the specified requirements.
consistence*	Relative mobility, or ability of freshly mixed concrete to flow i.e. an indication of workability.
cover	Distance between the outside face of the reinforcement and the nearest concrete face i.e. the external face of the deep foundation element.
deep foundation	Foundation type which transfers structural loads through layers of weak ground into suitable bearing strata (piles and barrettes). In this Guide also refers to specialist retaining walls such as diaphragm walls and secant pile walls.
defect	An imperfection which is deemed to require repair before incorporation into the permanent works.
diaphragm wall	Wall comprising plain or reinforced concrete, normally consisting of a series of discrete abutting panels. In this Guide also referred to as deep foundation. See Figure 1.
durability	Ability of material (e.g. concrete) to resist weathering action, chemical attack, abrasion, and other service conditions.
fines	Sum of solid material in fresh concrete with particle sizes less than or equal to 0.125 mm [120 mesh].
filling ability	The ability of fresh concrete to flow and fill all spaces within the excavation.
filter cake	Formation of a cake of filtered material, such as bentonite and excavated soil from a suspension, built up in the transition zone to a permeable medium, by water drainage due to pressure.
filtration	Mechanism of separating solids and fluid from a support fluid or from a concrete which has not yet set, where the surrounding, permeable ground under hydrostatic pressure is acting as a filter, analogous to filtration in supporting fluids.

TERMINOLOGY	DEFINITION
flow retention	See workability retention.
flowability	The ease of flow of fresh concrete when unconfined by formwork and/or reinforcement.
fresh concrete	Concrete which is fully mixed and is still in a condition that is capable of being placed by the chosen method. See tremie concrete.
identity testing	On-site testing during execution of the works to verify the identity of the concrete delivered, including the acceptability.
imperfection	Any deviation in the planned shape or material within the foundation that may or may not affect foundation performance.
interface layer	Layer considered to accumulate between the support fluid and the concrete, possibly formed by material from segregated concrete and/or support fluid with soil particles and/or material scraped from the walls by the rising concrete.
panel	Section of a diaphragm wall that is concreted as a single unit. It may be linear, T-shaped, L-shaped, or of other configuration. See Figure 1.
passing ability	Ability of fresh concrete to flow through tight openings such as spaces between steel reinforcing bars without segregation or blocking.
paste	The part of concrete usually referred to as cement paste, consisting of fines, water, admixtures, and air, without aggregates.
plastic viscosity	Viscosity of a Bingham fluid (with non-zero shear stress).
rheology	Study of the deformation and, in particular in this Guide, the flow of a substance under the effect of an applied shear stress
robustness (of fresh concrete)	Ability of the concrete mix to maintain the fresh properties pre- and post-casting despite minor acceptable variations in batching accuracy and raw material properties.
segregation resistance	Ability of concrete to remain homogeneous in composition while in its fresh state.
sensitivity	Lack of robustness (see robustness)
service life	Assumed period for which a structure, or part of it, is to be used for its intended purpose with anticipated maintenance but without major repair being necessary (defined as "design working life" in EN206).
slump flow (spread)	The result of a test carried out in accordance with EN 12350-8 or ASTM C1611
slump retention	See workability retention.
specification (for concrete)	Final compilation of documented technical requirements given to the Concrete Producer in terms of performance or composition.
specifier	Person or body establishing the specification for the fresh and hardened concrete.
stability	Resistance of a concrete to segregation, bleeding and filtration.
stop end (joint former)	A form, usually of steel or concrete, placed at the end(s) of a diaphragm wall panel to create a joint; a waterbar may be incorporated at the joint.
suitability testing	Laboratory testing undertaken prior to commencement of the project to determine a concrete mix which balances the requirements for the properties of fresh and hardened concrete.
support fluid	Fluid used during excavation to support the sides of a trench or bored pile (drilled shaft). See also EFFC/DFI Support Fluid Guide.

TERMINOLOGY	DEFINITION
thixotropy	The tendency of a material to progressive loss of flowability when allowed to rest undisturbed but to regain its flowability when sufficient shear stress is applied.
tremie concrete	Concrete with the ability to achieve sufficient compaction by gravity when placed by tremie pipe in a deep foundation, under submerged conditions.
tremie pipe / tremie	Segmental pipe with waterproof joints.
tremie method (submerged concrete placement or slurry displacement method)	Concrete pouring method by use of a tremie pipe in order to prevent the concrete from segregation or contamination by the fluid inside the excavation, where the tremie pipe - after the initial placement - remains immersed in previously poured, workable concrete until the completion of the concreting process.
viscosity	Measure of a fluid's resistance to shear strain, specifically the resistance to flow of fresh concrete once flow has started.
workability*	The property of freshly mixed concrete which determines the ease with which it can be mixed, poured, compacted, and finished.
workability retention	Retention of specified properties of fresh concrete, such as flow and slump, for a specified duration of time.
yield stress	Shear stress required to be reached to initiate flow.

***** Note:*** *Within European Standards, the word 'consistence' has replaced 'workability' but this is not the case in the US.*

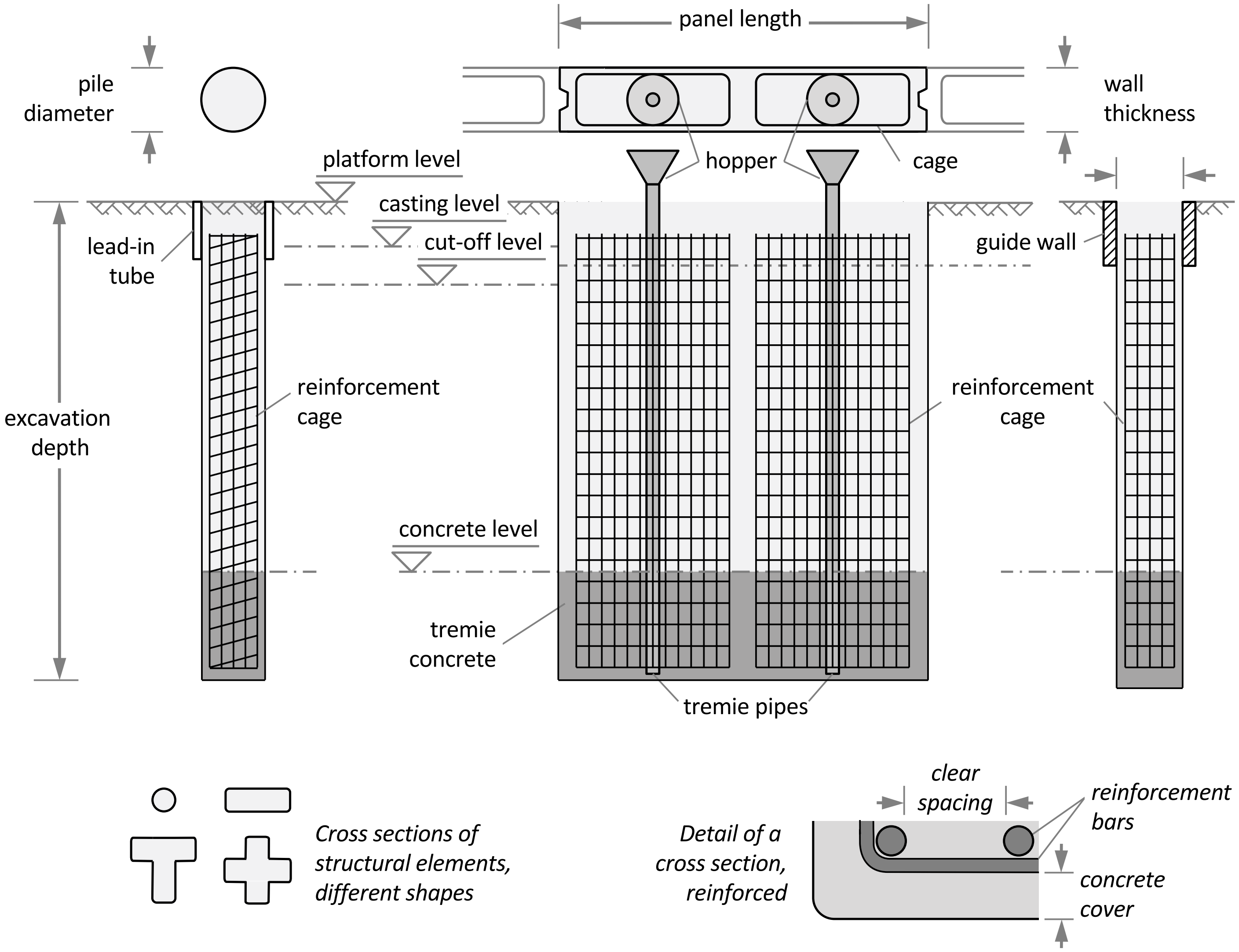
Within this Guide, the following equivalents apply:-

- *Consistence: measured from tests such as slump-flow (EN 12350-8).*
- *Workability: set of fresh concrete characteristics i.e. flowing, passing and filling ability including consistence (see Figure 4).*

List of Abbreviations and Symbols

AASHTO	American Association of State and Highway Transportation Officials
ACI	American Concrete Institute
ADSC-IAFD	The International Association of Foundation Drilling
AFNOR	Association Française de Normalisation
API	American Petroleum Institute
ASTM	ASTM International
CEN	European Committee for Standardization
CIA	Concrete Institute of Australia
CIRIA	Construction Industry Research and Information Association (UK organisation)
DAfStb	Deutscher Ausschuss für Stahlbeton (German Committee for Structural Concrete)
DIN	Deutsches Institut für Normung (German Institute for Standardization)
DFI	Deep Foundations Institute
ECPC	Equivalent Concrete Performance Concept
EFFC	European Federation of Foundation Contractors
EN	European Norm (see also prEN)
EPCC	Equivalent Performance of Combinations Concept
FHWA	Federal Highway Administration
GGBS/GGBFS	Ground granulated blast furnace slag
ICE	Institution of Civil Engineers (UK Professional Body)
ISO	International Organization for Standardization
NF	Norme Française
ÖBV	Österreichische Bautechnik Vereinigung (en: Austrian Society for Construction Technology)
prEN	A draft European Norm issued for comment before acceptance
QA/QC	Quality Assurance/Quality Control
R & D	Research and Development
SCC	Self-Compacting Concrete
VSI	Visual Stability Index
a	minimum clear spacing between reinforcement bars
c_{min}	minimum concrete cover according to structural or execution requirements
c_{nom}	nominal concrete cover = $c_{min} + \Delta c_{dev}$ (to be considered in design)
Δc_{dev}	allowance in design for construction tolerance
Δd_{cage}	additional allowance in reinforcement cage design for installation
$d_{b\text{-}t}$	distance from bottom of excavation to tremie pipe outlet
d_{spacer}	horizontal dimension of the spacer (perpendicular to reinforcement cage)
D	dimension (diameter or thickness) of excavation or concrete element
D_{cage}	outer dimension of the reinforcement cage
D_{final}	diameter of the final spread of the concrete achieved in a slump flow test
D_{max}	maximum nominal upper aggregate size
D_{nom}	nominal excavation dimension, defined by excavation tool dimensions
D_s	reinforcement bar diameter
$D_{s,n}$	substitute diameter for a bundle of 'n' reinforcement bars
D_T	internal diameter of tremie pipe
η	dynamic viscosity
h_1/h_2	embedment of tremie pipe before (h_1) and after (h_2) tremie pipe is cut
h_c	concrete level in excavation
$h_{c,T}$	concrete level in tremie pipe (= hydrostatic balance point)
h_F	fluid level in excavation
k	factor which takes into account the activity of a Type II addition
μ	plastic viscosity
$p_{i,T}$	hydrostatic pressure inside tremie pipe
p_o/p_i	hydrostatic pressure outside (p_o) and inside (p_i) the excavation
s_T	section length of tremie pipe section to cut
t_{final}	time for concrete to reach final spread in slump-flow test
τ	shear stress
τ_0	yield stress
$\dot{\gamma}$	shear rate

FIGURE 01 EXAMPLES OF DEEP FOUNDATIONS



Section 1

General

1 / General

1.1 Background

Concrete technology continues to advance rapidly and modern mixes with five constituents – cement, additions, aggregates, (chemical) admixtures and water – often have characteristics which differ significantly from the older three-constituent concrete mixes – cement, aggregates and water. Trends favour multi-component cements and higher strength classes and lower water/cement ratios, resulting in greater dependence on admixtures to compensate for reduced workability and to meet the (often competing) demands for workability in the fresh state and setting time. The application of testing the true rheological properties of the concrete has not developed at the same rate as the concrete mixes themselves and it is still not uncommon for the workability (e.g. measured by slump) to be used as the only property for acceptance of the fresh concrete.

A joint review of anomalies, imperfections, and defects observed after completion in bored piles and diaphragm walls cast using tremie methods by both the European Federation of Foundation Contractors (EFFC) and the Deep Foundations Institute in the United States (DFI) identified that a factor in a significant number of cases was the use of concrete mixes with inadequate workability, or insufficient stability or robustness. It further identified other causes as inadequate concrete specifications and inadequate testing procedures. The consequences of these problems are often significant and it was recognised that, besides the selection of suitable concrete constituents and appropriate concrete placement methods, developing suitable and robust concrete mixes is absolutely essential, as well as appropriate testing methods to ensure compliance.

A joint Concrete Task Group was established by EFFC and DFI in 2014 to look at these issues and Edition 1 of this Guide was published in 2016.

A research and development project, funded by the Sponsors of this Guide, was carried out from 2015 to 2018 by the Technical University of Munich in conjunction with the Missouri University of Science and Technology. This project included desk studies, laboratory testing, and on-site testing at worksites in Europe and the US. Furthermore, the Task Group has reviewed and evaluated state-of-the-art computational methods to numerically simulate concrete flow in deep excavations with academic partners from universities.

1.2 Purpose and Scope

The primary purpose of this Guide is to give guidance on fresh concrete characterisation with respect to its performance, the concrete mix design process, and the methods used to test the fresh concrete. The principles of this Guide apply to tremie concrete for deep foundations but may also be applied for other forms of deep foundations (e.g. continuous flight auger piling).

The Guide addresses design considerations including concrete rheology, concrete mix design, reinforcement detailing, concrete cover and good practice rules for concrete placement. A review of methods to test the as-built elements is presented together with advice on the identification and interpretation of the results.

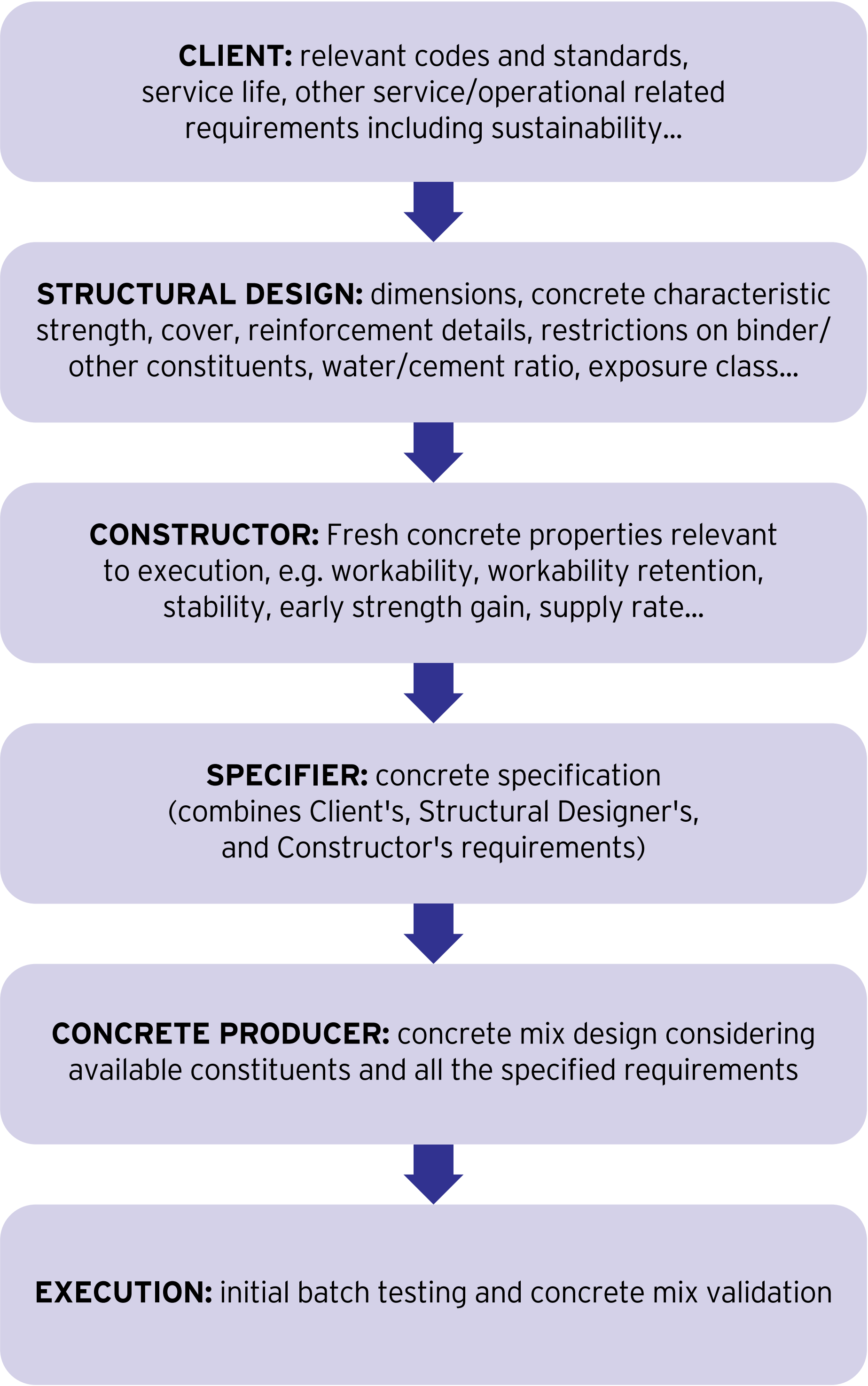
Figure 2 summarises how the demanding and often conflicting requirements should be considered throughout the development of a concrete mix. This Guide highlights the important areas that require careful consideration in order to minimise the potential risks, including the appropriate structural detailing and the use of state-of-the-art execution methods.

Getting the mix right can best be achieved via a joint approach between the Constructor, the Structural Designer, and the Concrete Producer.

The Task Group has now carried out detailed assessments of current good practice, research, and the state of the art regarding numerical modelling of the parameters which drive the concrete flow within an excavation. It is hoped that this Guide will provide information for use in future European and American Standards.

This Third Edition of the Tremie Guide includes a general review of the Second Edition, comprises more specific advice on testing fresh concrete (in a completely revised Section 5.3), emphasises the Task Group's understanding of designing sustainable concrete (in a new Section 5.6), and gives an update on interpretation of concrete flow mechanisms made on the basis of numerical modelling (in a revised Section 9, now supplemented by a new Appendix G). This Third Edition replaces the Second Edition.

FIGURE 02 TYPICAL EVOLUTION OF CONCRETE MIXES



CLIENT: relevant codes and standards, service life, other service/operational related requirements including sustainability...

STRUCTURAL DESIGN: dimensions, concrete characteristic strength, cover, reinforcement details, restrictions on binder/ other constituents, water/cement ratio, exposure class...

CONSTRUCTOR: Fresh concrete properties relevant to execution, e.g. workability, workability retention, stability, early strength gain, supply rate...

SPECIFIER: concrete specification (combines Client's, Structural Designer's, and Constructor's requirements)

CONCRETE PRODUCER: concrete mix design considering available constituents and all the specified requirements

EXECUTION: initial batch testing and concrete mix validation

This Guide will assist individuals and corporations involved in the procurement, design, and construction of bored piles and diaphragm walls including Owners/Clients, Designers, General Contractors and Specialist Contractors. It is intended as a practical addition to existing standards, not a substitute. Project specifications, Standards and Codes should always take precedence.

Section 2

Design Considerations Impacting Concrete Flow

2.1 General

The structural design of deep foundations is a specialist subject requiring both structural and geotechnical input, as it must also consider the conditions for the execution of the deep foundation works. This section covers structural detailing and the impact of the reinforcement cage on the flow of the concrete through the reinforcement bars into the cover zone embedding the bars. The impact of concrete placement on end bearing and shaft friction is not considered in this Guide and reference should be made to Eurocode 7 (EN 1997-1) or relevant US standards e.g. FHWA GEC10.

With regards to the reinforcement detailing, the ideal situation for tremie concrete placement is for there to be no obstructions to concrete flow. Unfortunately the reinforcement cage, including spacer blocks and box-outs (when used), represents a major obstruction to flow. The structural design, including the design of the reinforcement cage, therefore has a significant effect on the quality of the finished element.

The following sections give good practice recommendations for clear reinforcement spacing and cover. The Structural Designer of the reinforcement cage should consider the requirements for successful concrete placement specific to their design as well as the minimum general requirements given in Standards i.e. the structural design must meet the needs of the designer plus the constructor in exactly the same way as the concrete mix design. This may require the designer to seek specialist advice.

2.2 Clear Reinforcement Spacing

The clear reinforcement spacing (shown as ‘a’ in *Figure 3*) must be assessed by the Structural Designer based on the structural requirements and the ability of the concrete to flow through the horizontal and vertical bars of the reinforcement cage.

According to Eurocode 2 (EN 1992-1) the structurally required clear spacing between vertical bars or bundles of bars should be double their diameter D_s or nominal diameter $D_{s,n}$ (see *Table E.1* in *Appendix E*).

For execution the minimum clear spacing must respect two requirements, both with regard to the concrete. The first is to allow the concrete – understood as a Bingham fluid – to flow through the reinforcement (min a) and the second is to avoid blocking by the concrete’s aggregate (4 x D_{max}):-

$$a \geq \max \begin{bmatrix} \min a \\ 4 \times D_{max} \end{bmatrix}$$

ACI 336.1 requires a minimum clear spacing, min a, for vertical bars of greater than or equal to 100 mm [4 in], including lap zones, or four times the maximum aggregate size, D_{max}, whichever is greater. EN 206, EN 1536 and EN 1538 mirror the ACI requirements except that they allow a reduced clear spacing on vertical bars of 80 mm [3 in] at splice zones, provided that the second requirement to maximum aggregate size is met. These and further requirements are summarised in *Table E.1* and *Table E.2* in *Appendix E*.

In order to ensure flow of concrete into the cover zone, it is recommended that the minimum clear spacing on vertical bars is 100 mm [4 in], even in splice zones. This can be achieved either by increasing the clear spacing outside the splice zone, using couplers, or cranking the vertical bars so that the overlap is radial from the centre of the element.

The clear spacing of the horizontal reinforcement should be considered separately as these bars can restrict the horizontal and the vertical flow of the concrete, and should be 200 mm [8 in] for optimising concrete flow. Reference must be made to normative requirements, which are also summarised for minimum clear spacing for horizontal bars in *Table E.1* and *Table E.2* in *Appendix E*.

Multiple layer reinforcement should be avoided to reduce the risk of adverse effects on concrete flow. Multiple layers should be replaced wherever possible by bar bundles, larger bar diameters or higher-grade steel. If multiple layers cannot be avoided the minimum clear spacing, min a, should be increased.

Very high steel densities in deep foundation elements are often an indicator that the element size needs to be increased, and in extreme cases, full scale trials are recommended (see *Section 7*).

Note: Besides the risk reduction with regards to the quality and integrity of the final product, increased element sizes may also prove cost effective, dependent on the relative costs of the concrete and the reinforcement. In addition to the structural reinforcement requirements, additional temporary supporting steel is often required leading to congestion that may impede concrete flow.

Bending tolerances for reinforcement manufacturing should also be considered within the structural design.

2.3 Concrete Cover

Regarding the concrete cover for deep foundations, there are two independent requirements to be considered at the design stage. The first requirement covers the need for a certain concrete cover during the structure's service life and the second is the need for a minimum concrete cover during execution to allow for concrete flow and the removal of temporary casing. These two approaches are independent and therefore not necessarily compatible.

Both requirements, structural and for execution, have to be considered in the design when specifying the nominal cover, c_{nom}. The nominal cover is based on the required minimum cover, c_{min}, plus an allowance for construction tolerances, Δc_{dev}, as shown in *Figure 3*.

$$c_{nom} = c_{min} + \Delta c_{dev} \quad \text{with} \quad c_{min} \geq \max \begin{bmatrix} c_{min,\ structural} \\ c_{min,\ execution} \end{bmatrix}$$

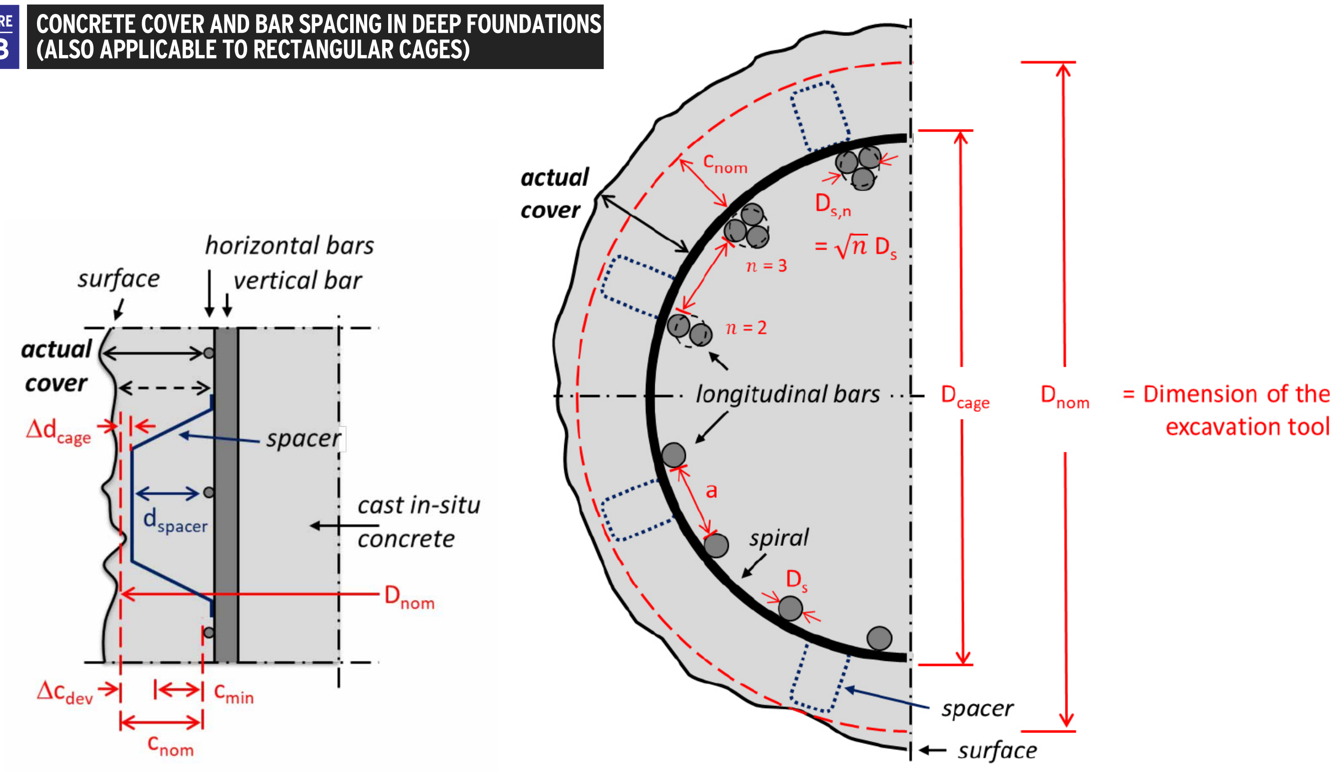
For execution, a nominal concrete cover of at least 75 mm [3 in] is recommended, which takes into account a minimum cover (c_{min}) of 50 mm [2 in] and an allowance for construction tolerances (Δc_{dev}) of 25 mm [1 in]. In most cases, the minimum nominal cover for execution will exceed those derived from structural and durability requirements.

Note: In Appendix E the present variation of normative rules is discussed in more detail. EN 1536 and the FHWA GEC 10 also identify particular instances where the minimum nominal cover must or should be increased.

Spacers are usually detailed to cover the design nominal cover. It should also be recognised that an additional tolerance, Δd_c, should be considered in the cage design to allow the installation of the cage into the excavation (see *Figure 3*):

$$D_{cage} = D_{nom} - 2\ c_{nom} - 2\ \Delta d_{cage}$$

FIGURE 03 CONCRETE COVER AND BAR SPACING IN DEEP FOUNDATIONS (ALSO APPLICABLE TO RECTANGULAR CAGES)



Note: The specific case of a bored pile constructed using a temporary casing is shown and discussed in Appendix E.

Section 3

Properties of Tremie Concrete

3 / Properties of Tremie Concrete

3.1 General

The rheology of concrete is fundamental to its behaviour during casting. Rheology determines the success of concrete placement and the quality of the final product i.e. durability is a direct function of rheology.

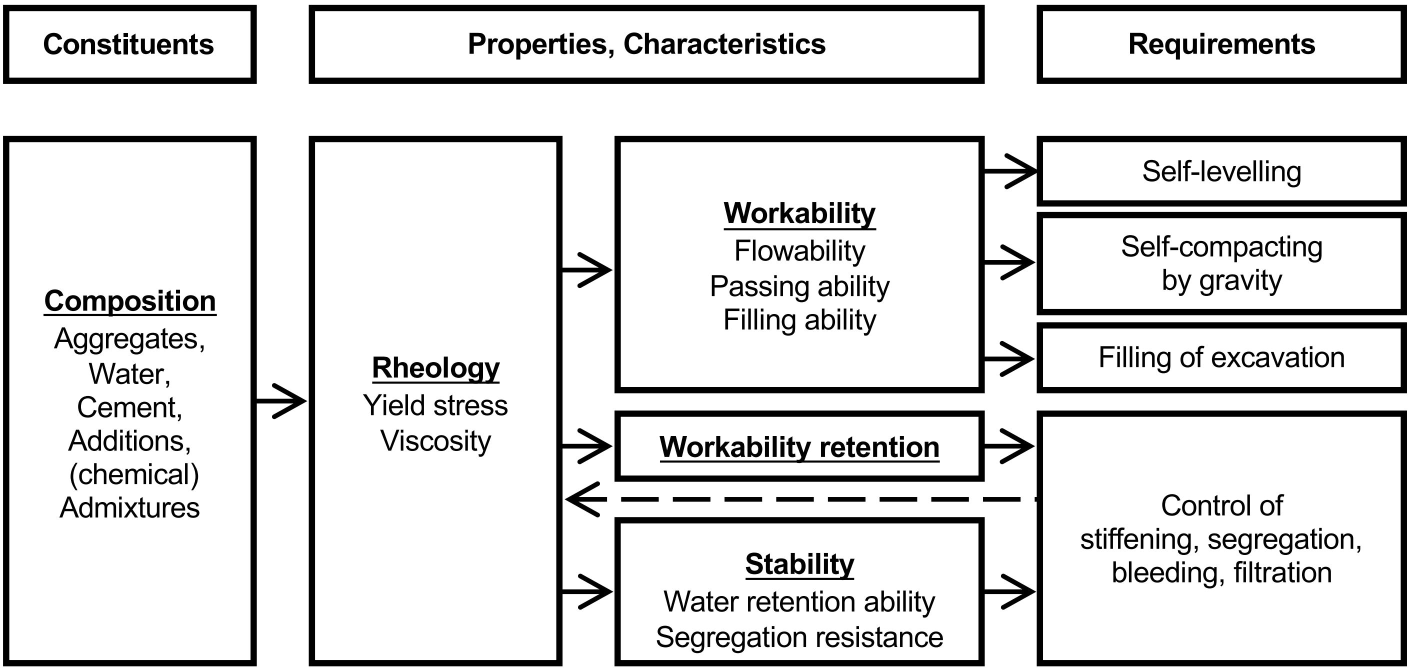
The key rheological characteristics for fresh concrete are:-

- Workability (the general term defining the ability of the concrete to fill the excavation, self-levelling and self-compacting under gravity)
- Workability retention (defining how long the specified fresh properties will be retained)
- Stability (resistance to segregation, bleeding and filtration)

Over recent decades, concrete as a construction material has evolved significantly. Concrete designs normally include durability requirements in addition to strength parameters and as durability and strength are, for a given concrete mix (of constituents), directly related to each other, there is a tendency to specify higher strength classes and lower water/cement ratios. This results in greater dependence on chemical admixtures to compensate for the reduced water content, the associated reduction in workability, and to meet the often competing specification demands for workability, stability, and flow retention. Insufficient stability or flow retention can affect the workability. The relationship between constituents, fundamental rheological properties, general concrete characteristics and performance requirements is illustrated in *Figure 4*.

There is very little guidance in current standards on the assessment of rheological behaviour. This chapter provides an explanation of concrete rheology and key parameters used to identify rheology.

FIGURE 04 DEPENDENCIES BETWEEN COMPOSITION, RHEOLOGY AND RELATED CHARACTERISTICS, AND OVERALL REQUIREMENTS



3.2 Rheology and Workability

To properly understand the behaviour of concrete in a fresh state, it is useful to consider it as a Bingham fluid model with the two parameters:-

- Yield stress, τ_0
- Plastic viscosity, μ

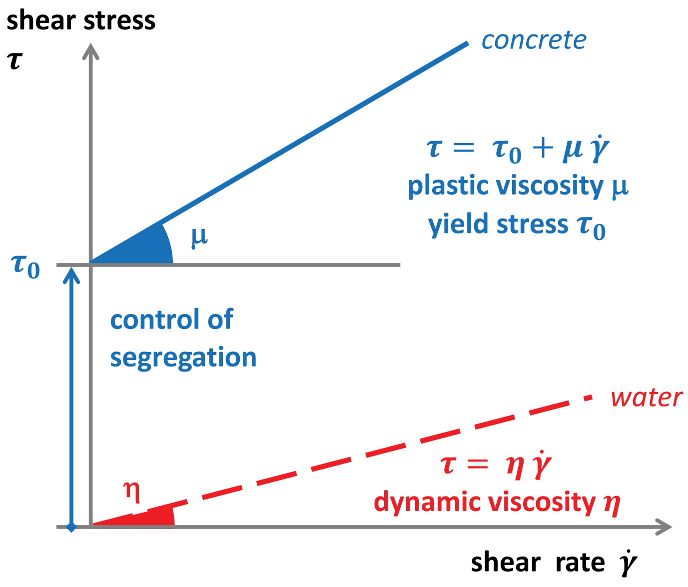
Yield stress is the shear stress required to be reached to initiate the flow of concrete. To control segregation the yield stress must not be too low. Conversely, to allow concrete to consolidate under gravity (without external vibration) the yield stress must not be too high.

Plastic viscosity is the slope of a Bingham fluid plot, as shown in *Figure 5*, and is a measure of its resistance to flow. It is related to the granular interaction and the viscosity of the paste between the aggregate particles. Successful placing of concrete requires low viscosity as this affects its distribution inside the excavation and also the time required to pour the concrete.

In practice, both yield stress and plastic viscosity will be time and shear history dependent.

Figure 5 demonstrates that concrete requires a certain amount of energy to start moving (the yield stress) and, thereafter, it resists this movement (by viscosity).

FIGURE 05 PLASTIC BEHAVIOUR OF A BINGHAM FLUID (E.G. CONCRETE) AND A NEWTONIAN FLUID (E.G. WATER)



Individual practical tests on the properties of fresh concrete currently used for conformity testing and control are unable to differentiate between the key rheological parameters (yield stress and plastic viscosity), which can only be determined with specialist laboratory apparatus (e.g. concrete rheometer). Until now, the ease of flow, as a measure for viscosity, has been assessed intuitively and qualitatively during concrete placement, for example, by observing and classifying the difficulty of emptying the tremie pipes or the concrete truck unloading times.

Note 1: In this Guide, both the dynamic viscosity and the plastic viscosity of a Bingham fluid are referred to using the general term 'viscosity'.

Note 2: The R & D program on rheology of Tremie Concrete in Europe and the US (Kraenkel and Gehlen, 2018) has proven a clear correlation between yield stress and plastic viscosity, evaluated by rheometer measurements, and values derived from simple and practical test methods. (See Section 5.2).

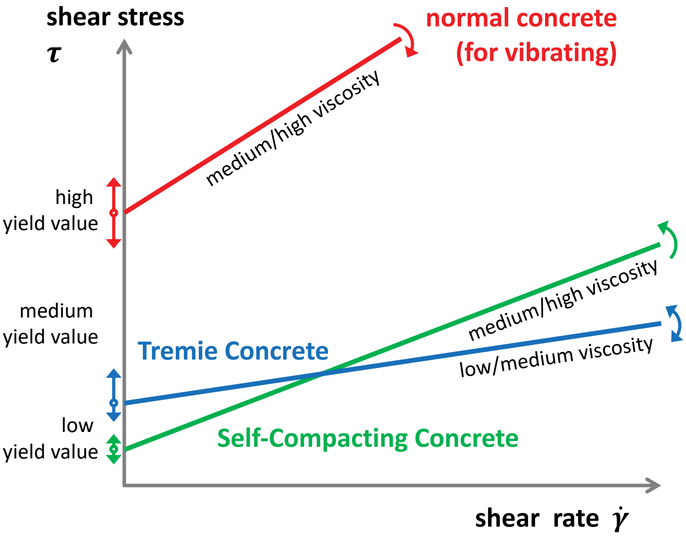
Figure 6 illustrates a qualitative comparison of rheology, represented by yield stress and viscosity, for different types of concrete and applications.

Normal concrete, compacted using mechanical means, has a relatively high yield stress whereas self-compacting concrete requires very low yield stress to achieve the requirement for self-levelling and compacting by self-weight alone. The yield stress of tremie concrete lies between the two and needs to be balanced between the relatively low yield stress required for a good filling ability, and the higher stress required to displace the support fluid and control segregation in deep foundations. The large concrete head, which exists during concrete placement in deep foundations, assists in compaction and makes it unnecessary to work with very low yield stress values which might result in sensitive concrete mixes.

Note: Tremie Concrete should never be considered as a type of Self-Compacting Concrete (SCC) for several reasons. The main reason is considered the fact that where SCC needs a low yield to allow self-levelling without any external force, Tremie Concrete needs a higher yield to control segregation over a longer period.

Viscosity may vary widely due to the actual concrete composition. In general terms viscosity should be low/medium for tremie concrete. This serves both to improve the ease with which concrete can flow around the reinforcement and other obstructions, and also reduces the time needed to complete a pour. In addition to general programme benefits, minimising pour durations avoids, or reduces as far as possible, the need for extended workability retention and any subsequent risk of increased concrete mix sensitivity.

FIGURE 06 QUALITATIVE COMPARISON OF RHEOLOGY FOR DIFFERENT TYPES OF CONCRETE

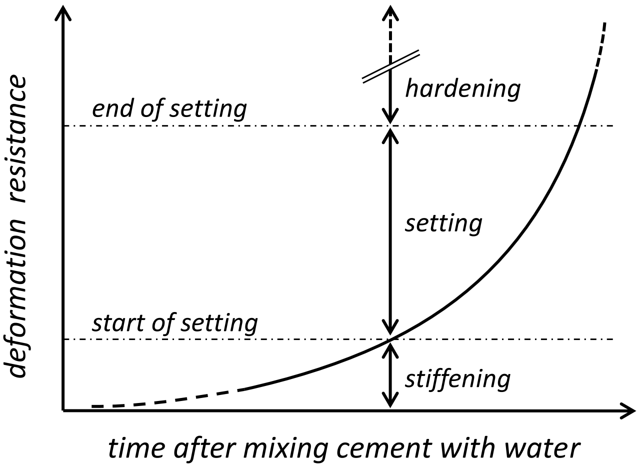


Concrete in the fresh state is considered a thixotropic material and it exhibits a form of stiffening which is reversible and flowability is regained when the material is agitated. This behaviour is caused by the settling and packing of particles when the concrete is at rest, and the consequent break-down of this structure when a shear stress is applied.

It is important that concrete thixotropy is controlled as excessive thixotropy could adversely affect concrete flow behaviour on resumption of concreting following a short interruption. There are currently no recognised measures or acceptance criteria. A practical measure could be to limit yield stress following a specified resting time, *see Appendices A.1.1, A3, A6, and A10*.

The workability retention must also be controlled as there is a point in time beyond which concrete should not be disturbed further as the stiffening is now due, primarily, to the hydration of cement and is irreversible (Roussel, 2012). This is illustrated in *Figure 7*.

FIGURE 07 STIFFENING AND SETTING TIME



3.3 Concrete Stability

Concrete stability is defined as its ability to retain water (filtration and bleed) and resistance to static segregation. The need to control stability should be balanced against requirements for workability.

Once the concrete is placed the strain rate drops to zero. It still retains its fresh rheological properties such as its yield stress but these will change over time e.g. due to a change in effect of the admixtures over time. Filtration, bleeding and static segregation can all continue whilst the concrete stiffens (see *Figures 7 and 13*). This is significant for concrete with longer setting times, especially concrete mixes for large pours with long workability retention.

Concrete stability can directly affect the quality and integrity of the final product, but also indirectly by impacting concrete flow mechanisms. Where concrete rheological properties have been affected by excessive filtration or bleed and the concrete is still required to move, i.e. being displaced by later poured concrete, it will affect the actual flow mechanism (see *Figure 4*).

There are two mechanisms for water loss from fresh concrete which can be broadly described as follows:-

- Filtration: separation of water from concrete due to 'squeezing' of concrete under applied pressure
- Bleeding: gravitationally driven separation of water from cement paste and aggregate matrix.

In practice some water loss from fresh concrete will always occur and is likely to be as a result of a combination of these mechanisms. Given that segregation cannot be totally eliminated, it is essential to understand both mechanisms in order to balance stability issues with workability. Further detail on filtration, bleeding and static segregation are provided below. *Section 4* of this Guide covering Concrete Mix Design outlines measures that can be taken to minimise stability issues.

Filtration

Fresh concrete in deep foundations is subject to high head pressures which in turn lead to high pore-water pressures in the fresh concrete, increasing with depth. These concrete pore-water pressures can be much higher than the water pressures in the surrounding ground. A hydraulic gradient develops and this leads to water flow out of the concrete into permeable soil layers. The effect of this water loss is to stiffen the concrete i.e. to change the rheological properties to higher yield stress and higher viscosity.

Filtration can be relevant in deep foundations where a reinforcement cage or plunge column has to be inserted after concreting is complete if the concrete can considerably stiffen due to the filtration water in the location of permeable soil strata. In these cases, filtration should be considered in the concrete design process.

Note: Work carried out by Azzi (2016) and Dairou et al. (2015) showed that the filtration loss can be used as an indication of the total bleeding potential (see section on Bleeding below). Further work is required to validate and define the boundary conditions (e.g the degree of consolidation in the concrete and the type of filter cake).

Appendix A provides information on testing the filtration of fresh concrete. *Section 5.3* recommends criteria for acceptance where relevant.

Bleeding

Bleeding of fresh concrete is a special form of segregation that occurs once the concrete has come to rest. Differences in specific gravity of the concrete constituents result in high water pressures in the fresh concrete which exceed the hydrostatic water pressures. This leads to a vertical hydraulic gradient which may allow the water in the cement paste to flow vertically towards the concrete surface. Preferential water flow pathways can also develop in concrete, often varying in size and frequency, depending on various parameters.

Note 1: Visible water flow pathways are often referred to as bleed channels (see Appendix D).

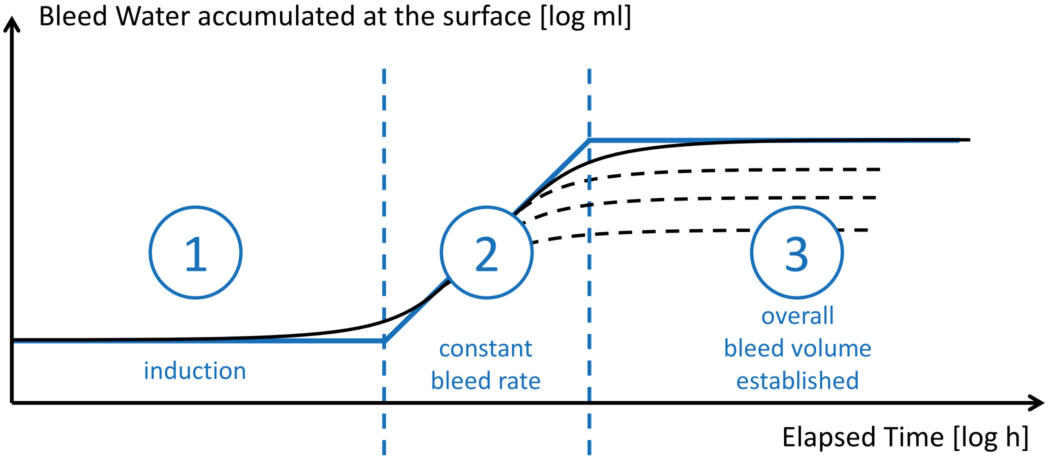
Note 2: The flow velocities in water pathways or bleed channels can be sufficient to transport fine grained aggregate and cement paste.

In order to limit the risk of anomalies created by the effects described above, bleeding should be controlled.

Research work by Massoussi et al, (2017) has identified the following three stages (see *Figure 8*):-

- An induction period
- A period of constant bleed rate
- A period where an overall bleed volume has been established

FIGURE 08 CONCEPTUAL DIAGRAM ON THE BLEEDING PROCESS IN CEMENT PASTES (BASED ON MASSOUSSI ET AL, 2017), WITH POSSIBLE INTERRUPTION OF BLEEDING DUE TO STIFFENING



The extent to which bleeding will occur in deep foundations depends on many factors including, but not limited to, the water to fines content, the aggregate particle size distribution, the efficiency of admixtures over time, the total concrete height and the time when the concrete reaches final consolidation. The time to commencement of bleeding and the following constant bleed rate are both essential to characterise the bleeding potential.

Note 1: Concrete may not reach its final consolidated state if bleeding is stopped by stiffening of the concrete before all potential bleed water has been expelled. A distinction can therefore be made between potential bleed and bleed which is realised under any particular drainage conditions.

Note 2: Bleed water might be (partially) re-absorbed due to hydration of the cement.

Note 3: Small-scale bleeding tests, as described in Appendix A, cannot be directly related to the full-scale processes in deep foundations. Filtration tests under positive pressure may be helpful in determining the overall bleeding potential.

Appendix A provides information on testing for bleeding of fresh concrete, and *Section 5.3* recommends criteria for acceptance where relevant.

While bleeding is a fundamental concrete characteristic, it is bleeding under very high concrete pressure heads that is of most relevance to tremie concretes. This results in large water pressures in the concrete, which are significantly greater than the hydrostatic water pressure. Therefore, when bleeding tests are considered necessary as part of the suitability testing both bleeding and filtration (under pressure) should be tested.

Segregation

Fresh concrete in deep foundations relies on its yield strength to maintain its stability once it is placed. In concrete with relatively low yield stress the relatively dense and large aggregate particles may sink through the lighter cement paste. This leads to a gradation of materials in the concrete. This process is known as static segregation.

Note 1: Case histories of static segregation are provided by Thorp et al (2018), where a heavily retarded concrete mix (delayed setting time) was evaluated for its static segregation after hardening (see Appendix A.8).

Note 2: There may also be segregation due to dynamic effects during transport and placement. Dynamic segregation is the mechanism where the concrete mix loses its homogeneity. In turn, a sufficient resistance to dynamic effects is considered to be covered by an appropriate composition and cohesion of the tremie concrete.

Appendix A provides information on testing the static segregation of fresh concrete, and *Section 5.3* recommends criteria for acceptance where relevant.

Section 4

Concrete Mix Design

4 / Concrete Mix Design

4.1 Introduction

It is not within the scope of this Guide to discuss the general principles of concrete mix design and proportioning of constituents. The reader should refer to one of the standard texts for a comprehensive coverage of relevant issues e.g. 'Concrete Technology' by Neville and Brooks (2010).

Typical steps in developing a concrete mix design are as follows:-

1. Starting from the required characteristic mechanical property, usually unconfined compressive strength (UCS), defining the average UCS, based on statistical considerations (previous experience and expected standard deviation).
2. Selecting the maximum aggregate size, based on reinforcement spacing (and other provisions in place). With regards to detailing (clear spacings between bars, cover etc.) reviewing the proportioning with special focus on suitable workability.
3. Proportioning of binder constituents based on strength and durability requirements. Considering replacement of cement by additions for limiting the heat of hydration and the thermal gradients in large structural elements, and/or for economic reasons.
4. Selecting the water/cement ratio, based on structural and durability requirements.
5. Selecting the necessary workability, based on the method of concrete placement.
6. Estimating the necessary quantity of mixing water, based on workability, maximum grain size and shape of aggregate, air content, and use of water reducing admixture.
   Note: Air entrainment admixtures should not be used for tremie concrete as the air will be compressed in deep foundations which may change the concrete properties (Feys, 2018)
7. Computing the necessary weight of cement (or binder), based on selected water/cement ratio and necessary mixing water.
8. Calculating the total amount of aggregates, by differential volume, and their particle size distribution, based on sand fineness.
9. Evaluating the type and amount of admixture to be added, to regulate the concrete workability time, depending on temperature and total time required for delivery and placement.
10. Evaluating the type and amount of other admixtures to be added, to adjust (rheological) fresh concrete performance and/or other characteristics.

Concrete Producers normally have a range of established concrete mix designs. One of these may be used as a starting point and modified as necessary.

The comments made in *Sections 4.2*, *4.3* and *4.4* are intended to highlight critical issues relevant to tremie concrete.

4.2 Concrete Mix Design Considerations

Concrete mix design is a complex process, which must balance the requirements of the specification with the available constituents. The selection and proportioning of constituents should include the following:-

- Concrete specification
- Material availability, variability and economics
- Concrete mixing plant efficiency and control capability of the production plant
- Ambient conditions expected at time of concrete placement
- Logistics of concrete production, delivery, and placement

Subsequent to the above assessment the initial selection of constituents and tentative proportioning should consider the following:-

- Compressive strength and durability (and any other design properties)
- Sufficient workability and workability time/retention
- Mix stability (resistance to segregation including bleeding)
- Aggregate source, maximum size, shape (crushed or rounded) and particle size distribution
- Cement content and composition
- Use of additions and their combinations (see *Appendix B* for concepts for Type II additions)
- Free water content
- Water/cement ratio
- Suitable admixtures
- Sensitivity of the concrete mix to variations in the constituents (i.e. its reproducibility in normal production)

Other design properties can result out of an extraordinary demand on durability, perhaps from a specific Service Life Design study. Particular requirements then have to be taken into account e.g. a limited chloride diffusion coefficient. A subsequent demand for special constituents, higher dosages of super-fine additions, an extra low water/cement ratio or similar, will in turn affect the fresh concrete properties. Conflicting requirements for durability and execution have to be balanced through the concrete mix design process.

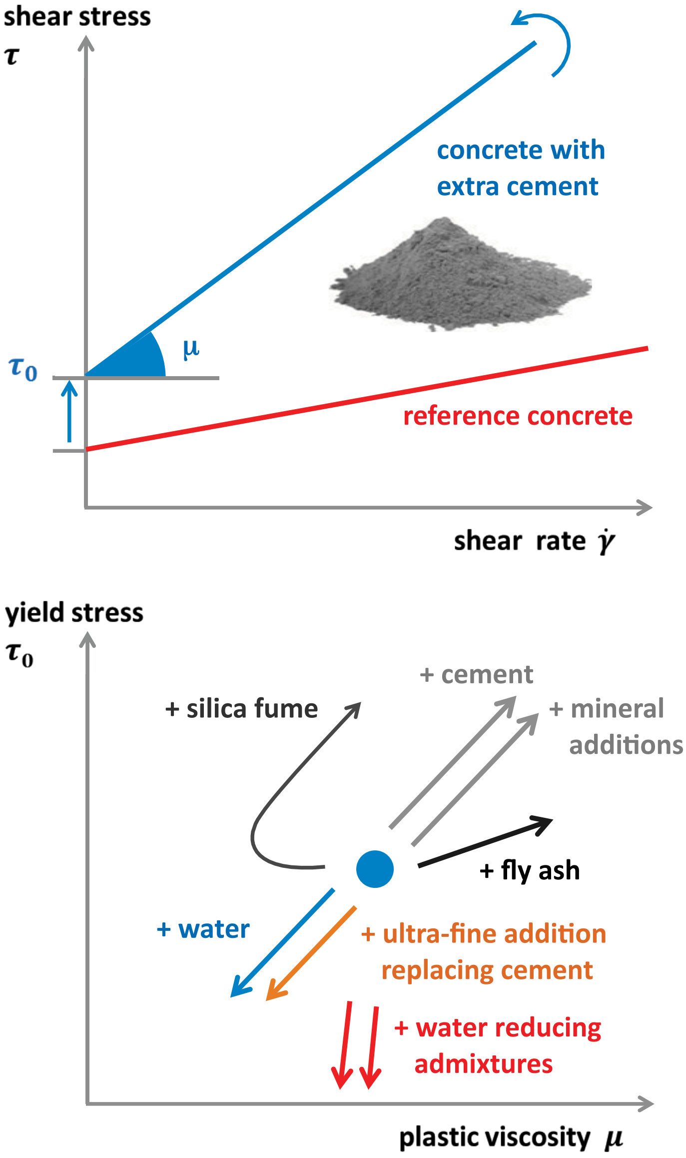
Concrete mix design development will normally start in the laboratory and following satisfactory laboratory trials and sensitivity studies will move to the field for full scale trials and development, and final approval by all relevant parties, including the determination of acceptance criteria for on-site testing.

4.3 Materials

Concrete rheology is influenced by all constituents and their proportioning, in particular by aggregate properties, particle shape and size distribution, cement and addition type and content, water/cement ratio and admixture types and doses.

The influence of cementitious additions on the rheological behaviour of concrete is shown in *Figure 9* (top), leading to a higher yield stress, and to a higher viscosity. The influence of various concrete constituents on both yield stress and viscosity is illustrated in a rheograph in *Figure 9* (bottom).

FIGURE 09 INFLUENCE OF CEMENT AND OTHER CONCRETE CONSTITUENTS ON RHEOLOGY (BASED ON WALLEVIK, 2003)



A concrete mix must comply with the requirements of standards and specifications applicable to the project e.g. water/cement-ratio, fines content, compressive strength etc.

In order to obtain a more workable concrete mix i.e. to decrease the viscosity and/or the yield stress, some suitable measures could be:-

- Replacing the cement partly with ultra-fine additions (significantly finer than the cement).
- Adjusting the aggregate particle size distribution.
- Adding water reducing admixtures (plasticiser or super-plasticiser).
- Increasing the water quantity or paste volume.

Note: It is good practice to limit the percentage of water-reducing admixtures in order to avoid excessive sensitivity to small variations in water content or other constituents e.g. sand, which in turn may lead to insufficient robustness of the concrete mix.

In order to obtain a more stable concrete mix i.e. to increase the viscosity and/or yield stress which would reduce a concrete's tendency to static segregation and bleeding, suitable measures can be:-

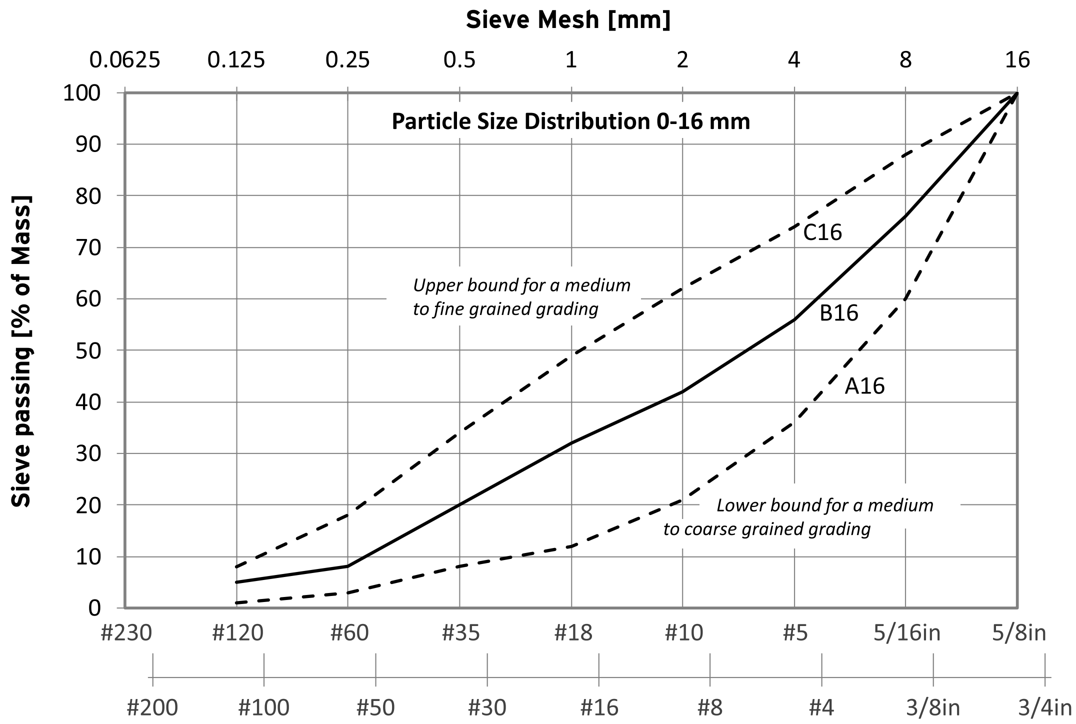
- Reducing water quantity and/or adding cement or filler, e.g. limestone powder.
- Adding fly ash, which generally has greater influence on viscosity than on yield stress.
- Adjusting the aggregate particle size distribution.
- Adding a viscosity modifying admixture.

Note: Silica fume can play a special role in that it is sometimes specified to achieve high performance such as extra durability. Up to a small percentage, silica fume may have a positive effect on workability (like ultra-fine filler) but the concrete will become more viscous and reach a higher yield stress at higher percentages i.e. silica fume can also have an adverse effect and reduce workability.

Selection and assessment of aggregate particle size distribution (grading) is an important element of concrete mix design, where grading is simply the division of an aggregate into fractions, each fraction consisting of one class of particle sizes. To minimise the risk or tendency for segregation, aggregates should be well graded (Dreux and Festa, 1998).

Figure 10 shows the typical range of aggregate particle size distributions for tremie concrete using maximum 16 mm [$^{5}/_{8}$ in] aggregate. It is recommended that the solid line is used as a starting point for the concrete mix design. Similar distributions for other maximum aggregate sizes are given in DIN 1045-2.

FIGURE 10 PARTICLE SIZE DISTRIBUTION (GRADING) FOR AGGREGATE WITH 16 MM [$^5/_8$ IN] MAXIMUM PARTICLE SIZE, AS STANDARDISED IN THE GERMAN NATIONAL ANNEX DIN 1045-2 TO EN 206-1



The Concrete Producer, when developing an appropriate aggregate particle size distribution (grading), should balance a number of factors:-

- The shape of the aggregate: (naturally) round shape supports the production of flowing concretes better than the more angular shape of crushed aggregate.
  Note: At the same grading and volume, the blocking resistance at reinforcement is considered higher for concrete with crushed aggregate, so that usually more (stable) paste is required for concrete using crushed aggregate.
- The size of the aggregate: a coarser grading (i.e. a higher proportion of larger aggregates) can give better workability but will also be more prone to segregation.
- The proportion of fine material: a higher proportion of fine material will give a more cohesive (higher yield) concrete mix.

Note: An excessive amount of fines may compromise workability due to its high water demand and may lead to higher required admixture dosages.

Whilst the beneficial effect of modern admixtures in the production of advanced concrete is recognised, the possible negative effect of admixtures should be understood. For example, reducing the quantity of water, by using water reducing admixtures, could in turn increase the viscosity. More paste might be needed to compensate for reduced workability. As a result of this, the yield stress of the bulk concrete will be reduced and the tendency for segregation increased.

In addition to the dosage of admixtures, their nature and operating mechanism can give rise to side effects such as a sticky appearance (high viscosity) or stiffening. Some combinations of cements and admixtures can cause a lack of robustness in fresh concrete, which could lead to excessive segregation (Aitcin and Flatt, 2015).

Detailed concrete mix design recommendations are outside the scope of this Guide. The emphasis in this Guide is to assess the performance of the fresh concrete using the test methods and recommended ranges given in *Section 5*.

4.4 Proportioning and Practical Considerations

Concrete mix limiting values should conform to European Standard EN 206 where the requirements of EN 1536 or EN 1538 have merged, or with the relevant local Standards or other standards specified for the project. FHWA GEC 10, in this context, is considered the US equivalent to EN 206.

Due to new developments or specific work conditions deviation from these standards may be considered; such as partial replacement of cement e.g. by fly ash or even the use of a lower cement content than the limiting value. Three concepts are available for the use and application of Type II additions or approved procedures for acknowledgment of equivalent performance (as described in *Appendix B*). These are:-

1. The k-value concept.
2. Equivalent concrete performance concept.
3. The equivalent performance of combinations concept.

Following initial development in the laboratory (suitability testing) it is advisable to carry out full size production field trials (field batching trials) to assess performance and check the suitability of specified properties. Suitable time periods should be allowed in contract programs to carry out the required testing.

The field batch testing and evaluation should be carried out or supported by qualified personnel. Care should be taken to verify that the conditions that existed during field batching trials continue to exist during construction. If conditions change (aggregate source, cement source, type or dosage of additions, chemical admixture, etc.), new trial concrete mix studies should be conducted to ensure that the target properties and performance will continue to be achieved (FHWA GEC10).

The required dosage of admixture should be determined by field batch trials where the conditions (ambient temperature, delivery times, concrete pouring techniques, etc.) expected during construction are replicated, and a sample of concrete is retained and tested to determine its workability retention characteristics. This trial-mixture study should also include workability testing to develop a graph of workability loss versus time after batching.

It is essential to control the mixing time to ensure that no uncontrolled effect of admixtures originates before or during the actual placement. Laboratory and field trial testing should help to ensure that the optimum dosage of admixture and mixing time is used in order to minimise potential risks.

The effectiveness of some super plasticisers is dependent on temperature and it is therefore important to check the mix over the full range of temperatures anticipated during the progress of the works. Without adjusting the dosages of retarding admixtures, an increase in temperature of about 10 °C [18 °F] will increase the rate of slump loss by a factor of approximately 2, which means that a slump loss graph made in the laboratory at 22 °C [72 °F] will be very misleading for concrete being poured in the field at higher temperatures of 32 °C [90 °F] (Tuthill, 1960).

It is common practice to adopt summer and winter concrete mixes with different doses of admixtures and minor adjustments to the cement content and water/cement ratio.

Special attention should be paid to the type of concrete mixing procedure at the concrete batching plant. In the wet mixing process, the constituents are all mixed in a centralised concrete mixer at the batching plant and then transferred to concrete trucks for delivery. In the dry mixing process, the dry constituents are discharged into the concrete truck and then water is added, with mixing taking place in the concrete truck.

In general, the wet mixing process is preferred over the dry mixing process for high performance concretes. It is however possible to supply high performance concrete using the dry mixing process but it is essential that the mixing time in the concrete truck is sufficient, especially during periods of high demand. It is recommended that detailed batch records with actual mixing time and quantities per truck load are obtained.

Testing of trial mixes in laboratory scale or, wherever possible, in full size batches should include an allowance for batching tolerances. Applicable test methods to characterise rheology including recommended ranges for acceptance are given in *Section 5*.

If the Concrete Producer needs to have the ability to make minor adjustments to the agreed mix design to achieve the required properties, then the extent of such adjustments should be agreed in advance. In the absence of any such agreement, the agreed concrete mix design should not be amended or changed by the Concrete Producer.

Section 5

Specifying and Testing of Concrete, Quality Control of Concrete Production, and Sustainability Aspects

5.1 A New Approach to Specifying Fresh Concrete

It is critical that the rheological properties of the tremie concrete are specified for the reasons described in *Section 3*. These properties should be established through concrete mix design development and rigorous suitability trials and appropriate conformity and identity testing to ensure that these properties are maintained throughout a project.

Current standard practice is to specify compressive strength, minimum cement content, maximum water/cement ratio, and workability. These limited parameters are insufficient to fully describe the required fresh properties for tremie concrete, particularly in terms of workability, workability retention and stability.

Note: European Standard EN 206 is under revision and a new Part 3 has been drafted to replace the Annex D of the current EN 206. The new EN 206-3 "Concrete – Additional provisions for concrete for special geotechnical works", acting together with EN 206-1, will allow for more detailed performance-based acceptance criteria to specify tremie concrete for its workability, workability retention and stability.

Additional requirements for the concrete should be given by the Specifier in terms of single target values, test methods and acceptance criteria as shown in *Section 5.3*.

There is general alignment within the Construction Industry of the need to design and construct in more sustainable ways. Within the deep foundations industry, concrete plays a very significant role in finding routes to improved sustainability. *Section 5.6* discusses measures and options which can be used to achieve this goal.

5.2 Test Methods to Characterise Fresh Concrete

Detailed research work by the Technical University of Munich and Missouri University of Science and Technology (Kraenkel and Gehlen, 2018) determined that the fundamental properties characterising concrete workability are yield stress and viscosity. As there are no practical field tests to measure these properties directly, indirect measurements are required. Both the slump-flow and slump-flow velocity tests described in *Appendix A.1* can be used to give an indirect measurement of the relevant characteristics as well as giving an indication of stability using the VSI test. *Figure 11* illustrates the correlation between yield stress and slump-flow. For typical situations, and with cage detailing well within the mandatory rules set out in *Section 2* and *Appendix E*, a target slump-flow value of 450 mm (with a tolerance of ±50 mm) could be adopted. For specifying other slump-flow target and tolerance values, refer to the Notes under *Table 2a* below. *Figure 12* shows the approximate correlation between viscosity and slump-flow velocity.

FIGURE 11

SLUMP-FLOW CURVE RELATED TO YIELD STRESS AND RECOMMENDED RANGE FOR TREMIE CONCRETE (SEE APPENDIX A.1.1 AND FIGURE 6)

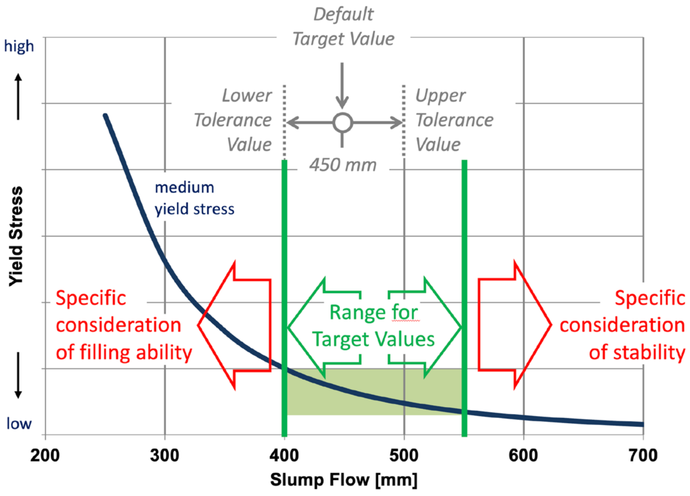
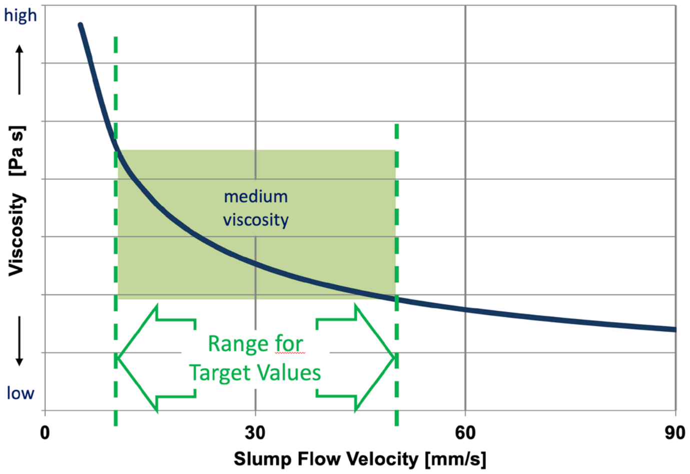


FIGURE 12

SLUMP-FLOW VELOCITY CURVE RELATED TO VISCOSITY SHOWING THE RECOMMENDED RANGE OF MEDIUM VISCOSITY FOR TREMIE CONCRETE (TEST SEE APPENDIX A.1.2)



In addition to the slump-flow, slump flow velocity and VSI combined test (*Appendix A.1*), other tests to characterise the fresh concrete with regard to workability, workability retention and stability are given in *Appendices A.2* to *A.10*. The relevance of these other tests is given in *Section 5.3*.

The slump test (*Appendix A.6*) and the flow table test (*Appendix A.7*) are standard tests to determine workability in accordance with EN 12350-2 and -5. Based on the work undertaken by Kraenkel and Gehlen, 2018, the slump-flow test gives a better correlation to the yield stress for tremie concrete than the slump and flow table test. In this Guide, the slump-flow is presented as the preferred parameter to represent yield stress.

Note: The L-box test may give a good indication on the passing ability of tremie concrete but this is deemed to be covered by the mandatory limitation of its maximum coarse aggregate. Due to the flow resistance to passing through the bars in the L-Box this test cannot directly be correlated with the rheological properties for tremie concrete and is therefore not recommended (Kraenkel and Gehlen, 2018).

5.3 Suitability, Conformity and Identity Testing

The purpose of the suitability testing is to find a concrete mix which balances the often conflicting requirements for the properties of fresh and hardened concrete i.e. workability, stability, workability retention time and/or thixotropy, rate of strength gain and durability. It is important to recognise that successful performance of a tremie concrete is determined by a suite of tests and no single test will adequately describe all the required characteristics. Suitability testing should be undertaken when the Concrete Producer cannot prove relevant experience for the concrete mix design as part of the initial test program. Suitability tests are recommended prior to commencement of the project as part of the pre-construction trials (plant trials) program.

Conformity testing is an integral part of the production control of the Concrete Producer (usually the supplier). The evaluation of conformity is the systematic examination to which the fresh concrete fulfils the specified requirements.

During execution of the deep foundation works, the on-site testing (identity testing) proves the acceptability of each load delivered. The identity testing should be carried out using slump-flow and Visual Stability Index on every load. The slump-flow velocity should be checked at least once per week as this is not as critical as the slump-flow. Other tests recommended to demonstrate conformity e.g. stability may be used as needed.

Table 01 lists all the tests appropriate for use with tremie concrete (see also *Appendix A*) and indicates the concrete characteristic for which the test is relevant.

TABLE 01 APPROPRIATE TESTS FOR TREMIE CONCRETE

No	Test	Reference standard*	Workability	Thixotropy**	Stability
A1.1	Slump-Flow	ASTM C1611	✔	✔*	-
A1.2	Slump-Flow Velocity**	EN 12350-8	✔	-	-
A1.3	VSI	ASTM C1611	-	-	✔
A2	Flow time	NF P18-469	✔	-	-
A3	Workability Retention	EN 12350-1	✔	-	-
A4	Bleeding	prEN 12350-13 ASTM C232	-	-	✔
A5	Filtration	prEN 12350-13	-	-	✔
A6	Slump	ASTM C143 EN 12350-2	✔	✔	-
A7	Flow Table	EN 12350-5	✔	✔	-
A8	Static Segregation	ASTM C1610	-	-	✔
A9	Sieve Segregation	EN 12350-11	-	-	✔
A10	Manual Vane Shear	-	✔	✔*	-

** Some tests are not strictly in accordance with European Standards or US Standards. Hence, not all Concrete Producers will be familiar with the properties specified and it may require specific agreement with the Concrete Producer on a case-by-case basis. Optional test methods are listed and described in Appendix A.*

*** Information on thixotropy can be obtained as outlined in Appendix A.3.*

Table 2a gives recommended suitability tests, target value ranges and tolerances. It also details the relevance of each for suitability testing. The Specifier should select from *Tables 2a and 2b* the required characteristics and specify these requirements to the Concrete Producer to be checked during the suitability testing.

TABLE 02a RECOMMENDATIONS FOR SUITABILITY TESTING

No	TEST	TARGET VALUE (from range)	TOLERANCE to specified Target Value	RELEVANCE for SUITABILITY
A1.1	Slump-Flow*	400 - 550 mm	± 50 mm	M
A1.2	Slump-Flow Velocity**	10 - 50 mm/s	± 5 mm/s	M
A1.3	VSI	0	-	M
A2	Flow time	3 - 6 s	± 1 s	M
A3	Workability Retention**	to be specified	to be specified	M
A4	Bleed Rate	≤0.1ml/min	+ 0.02 ml/min	M
A5.1	Bauer Filtration***	≤ 22 ml****	+ 3 ml	M
A5.2	Pressure Filtration	≤ 9mm/m	+2 mm/m	M
A8	Static Segregation	≤ 10%	+ 2%	R

M = Mandatory; R = Recommended

** Note: The chosen target value must be determined by the Specifier after an engineering assessment (by the Structural Designer and/or Constructor) of the specific details of the deep foundation element. The most important factors include the clear spacing of the vertical and horizontal reinforcement bars, the volume of the element, the estimated pouring time, and the depth. Some further factors are given in Appendix F. If the detailed assessment results in a requirement for high workability (e.g. slump-flow target of 550 mm [22 in]), then this may require additional testing to ensure that there are no stability issues. Conversely, where a low workability is deemed appropriate (e.g. slump-flow target of 400 mm [16 in]), then this may require additional testing to ensure filling ability with time i.e. workability retention. If a specific target value is not assessed, a target value of 450 mm is recommended.*

*** Note: Depending on concrete mix design, long workability retention time can be associated with delayed setting time of concrete. It is recommended that strength development starts early enough in order to ensure setting time and strength gain is suitable to limit bleeding potential of the concrete and allow for continuation of site operations. A minimum setting time and/or a minimum strength may be specified by a minimum strength after a given time.*

**** Note: Alternative tests are available as described in Appendices A.5.2, and A.5.3.*

*****Note: Higher filtration values may be acceptable based on previous experiences with similar mixes.*

Table 2b gives the required frequency of identity testing for tremie concrete.

TABLE 02b RECOMMENDATIONS FOR IDENTITY TESTING

No	TEST	Specified TARGET VALUE* [from range]	TOLERANCE to specified Target Value	RELEVANCE for CONFORMITY	FREQUENCY** of specified IDENTITY testing
A1.1	Slump-Flow	[400 - 550] mm*	± 50 mm	M	Each load
A1.2	Slump-Flow Velocity	[10 - 50] mm/s	± 5 mm/s	M	At least 1/week
A1.3	VSI	0	-	M	Each load

M = Mandatory

** Note: Based on the detailed engineering assessment.*

*** Note: Testing frequency may be reviewed once target values have been reliably and consistently achieved.*

It is the opinion of the Concrete Task Group that tests specified to establish suitability of the concrete mix design may require further controls during production for information and to anticipate deviation from concrete quality that is not generally captured by identity testing (workability at delivery and compressive strength).

Table 2c gives recommendations for additional testing during production and recommended frequency that can be incorporated in project ITP's (Inspection and Testing Plans). The results should be checked against specified values in accordance with *Tables 2a* and *2b*.

TABLE 02c RECOMMENDATIONS FOR ADDITIONAL IDENTITY TESTING

No	TEST	FREQUENCY* of additional IDENTITY testing
A2	Flow time	Min 1/day
A3	Workability Retention	Min 1/week
A4	Bleed Rate	Min 1/week
A5.1	Bauer Filtration /	Min 1/week
A5.2	Pressure Filtration	

** Note: Testing frequency may be reviewed once target values have been reliably and consistently achieved.*

5.4 Control of Workability Retention

It is important that the Specifier (see *Figure 2*) makes a realistic assessment of the period over which certain properties should be obtained, or the decrease of workability should be limited, especially for large pours (e.g. greater than 200 m^3 [260 cy]), where supply capacity is limited, or where supply is complex due to a congested site. This assessment should include consideration of the following:-

- Period required to pour the pile/panel
- Transport distance/time from plant to site
- Concrete plant capacity and materials control
- Availability of approved back-up facilities
- Concrete truck capacity and number of trucks
- Quality of site access
- Climatic conditions, in particular temperature
- Actual loss of workability over time, see *Tables 01* and *02* and *Appendix A.3*

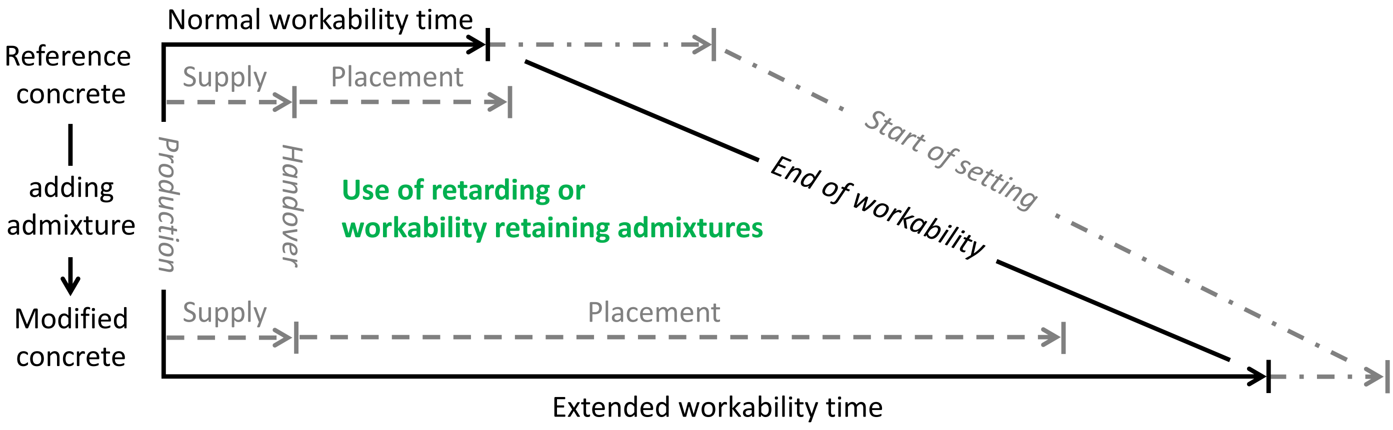
A detailed consideration of the above factors will often result in the requirement to extend the workability retention (or flow/ slump retention, sometimes also referred to as workability life or open life) using retarding or workability retaining admixtures, as illustrated in *Figure 13*.

The workability retention should be specified by a target value for slump-flow at a defined time after mixing. The procedure and apparatus required for transporting, handling, storing and remixing of samples should also be specified.

A detailed assessment for pours of deeper elements and estimated time for pouring carried out to determine if the above minimum workability may not be required at the end of the entire pour should be carried out as this depends on flow type and tremie removal rate. Detailed recommendations for such situations cannot be made at this time but should be addressed in future editions of this Guide, once extended numerical studies provide sufficient evidence for recommendations.

EN 12350-1 gives guidance on sampling of fresh concrete and assessment of workability retention as described in *Appendix A*. See also the equivalent ASTM standard(s).

FIGURE 13 EXTENSION OF WORKABILITY TIME



5.5 Quality Control on the Concrete Manufacturing Process

Concrete Producers should work in accordance with the specified contract requirements (in Europe, EN 206 and its related National Annex), and in the US ACI 211, ACI 301 and ACI 318). The Concrete Producer should have product conformity certification with the following minimum requirements, wherever possible, though there are remote areas where it may be difficult to find producers with product conformity certification:-

- An approved quality management system
- Product testing by or calibrated against a laboratory accredited for the tests undertaken
- Surveillance that includes checking the validity of the producer's declarations of conformity, by a certification accreditation body

Note 1: Conformity control shall be in accordance with the conformity control requirements for designed concretes specified e.g. EN 206.

Note 2: Provisions for assessment, surveillance and certification of production control by an accredited body should be as specified in relevant standards e.g. EN 206.

The manufacturing process plays a key role in the consistency of the batched concrete and is therefore most important for the performance of tremie concrete. It is good practice to be familiar with the Concrete Producer's design, manufacturing and quality control process, prior to ordering concrete. The Concrete Producer should inform the Specifier of the status of the concrete production plant at the time of tender and immediately if any change in status occurs during the period between the time of the order and the completion of supply.

In regions where Concrete Producers with the required level of product conformity certification are not available, it may be possible to use a Producer with a lower level of quality assurance. It may then be the responsibility of the customer to ensure the correct quality and consistency (i.e. uniformity) of concrete supplied. As a minimum, suitably experienced personnel should check (or assess) the following items:-

- Calibration of weighting sensors to ensure correct concrete mix proportions.
- The free moisture content of the aggregates.
  Note: Tremie concrete often contains a higher proportion of small aggregate than normal concretes and consequently the assumed free water content may be too low (Harrison, 2017)
- Calibration of flow meters where used for the addition of water etc.
  Note: Torque meters may be considered reliable for the intermediate ranges of workability.
- Method of measurement of admixtures.
- Calibration of moisture probes both, automatic where used to measure moisture contents in the fine aggregate, and hand held devices used to measure moisture content in the stock piles.

The following are considered good practice in order to supply tremie concrete with consistently suitable quality. Relevant requirements should be included in project specifications and include records for demonstration of conformity:-

- Moisture content of aggregates should be measured on a regular basis dependent on the volume of material being used, the weather conditions, the storage conditions, the sensitivity of the concrete mix etc. It should be noted that the moisture content of fine aggregate will vary more widely than that of coarse aggregate. It is common practice to adjust moisture content based on daily observation of coarse aggregate. Moisture content of fine aggregate will vary more widely and as a minimum should be checked for every load. However, modern batching plants normally have probes measuring moisture content of fine aggregate at the point of discharge to the concrete mixer (in-flight) and will adjust water demand accordingly. For major projects in-flight moisture probes should be specified.

Note 1: Monitoring of moisture content in the surface material of an aggregate bin that has not been recently disturbed may not be representative of the majority of the material in the bin.

Note 2: Surface moisture contents and absorption values for fine and coarse aggregates should be validated regularly by oven drying of representative samples.

Note 3: A consistent temperature and moisture content can be achieved by requiring aggregate to be conditioned for a minimum of 24 hours prior to batching.

- Control of the actual water content in fresh concrete should be made on a regular basis.

Note: Concrete is frequently batched using automatic controls that balance the volume of constituent added and the torque of the concrete mixer. For tremie concretes with high workability, these measurements may not be accurate enough and measurement of actual water content is preferred.

- Mixing water including any re-cycled water should be checked weekly for its fines content and chemical composition in order to ensure compliance with relevant standards e.g. US standard ASTM C1602 or EN 1008.

Note 1: The variation of re-cycled water may cause adverse effects on workability and therefore require additional admixtures to ensure the required workability is achieved. Workability retention should be retested if using recycled water.

Note 2: Some contractors are reluctant to accept recycled water due to their experiences with greater scattering of fresh concrete properties and effecting workability time, probably due to varying fines contents and/or varying remains from super-plasticisers.

- Fine and coarse aggregate gradation of representative samples should be checked weekly or every time the supply source is changed.
- The concrete mixer should be thoroughly cleaned at least once a day.
- Electronic copies of weigh batch records including mixing time should be printed directly for each concrete truck.

Note: All information needed by the user is on the delivery note and as there is a requirement for product conformity certification, the certification body as part of their routine practice will spot check that the batch records align with the specification (see Harrison, 2017 on interpreting batch records).

- The concrete truck mixers should be emptied of any residual concrete or water before being filled.

Note: It is the Specifier's responsibility to allow or prohibit the use of recycled materials. The Concrete Producer should be required to declare for approval any waste minimisation system. The use and control of recycled water, dust collection introduced to the concrete mixer or reclaimed aggregate should be identified and measured to control the content and the effect on the concrete.

The reproducibility of results for the tests recommended in *Appendices A.1.1 to A 1.3* depends on the qualification of laboratory technicians, and is partly based on their subjective judgements. Research is currently being undertaken investigating ways of reducing the significance of the 'human factor', for example by using 2D or 3D cameras, surface scanning and image processing techniques. The working group is confident that practical and affordable methods will be available in the medium term, including those that are suitable for construction sites.

5.6 Concrete Sustainability

All stakeholders involved in the procurement, design, and construction of deep foundation elements including Owners/Clients, Designers, General Contractors, Specialist Contractors and Concrete Producers have a shared obligation to address climate change and its impacts.

The significant consumption of raw materials and carbon emissions from the production of concrete is driving change in concrete composition. Concrete is evolving to contain multi-component cementitious materials, recycled/manufactured aggregates and new additives.

Discussion on rheological characteristics, mix design considerations and identity testing in this Guide are necessarily focused on tremie concrete performance criteria rather than specifying an actual concrete composition. To support future decarbonisation through the trial and adoption of evolving concrete mixes, the predominantly performance based tremie concrete mix design recommendations in this Guide may also provide a basis for investigating evolving tremie concrete mix designs.

It should however be recognised that concrete rheology is influenced by all its constituents and evolving tremie concrete mixes with new or substantial increases in constituents from current concrete mixes should be thoroughly assessed across the full range of suitability, conformity and identity testing in Section 5, to fully characterise the fresh and hardened concrete performance.

Good practice guidance on the wider decarbonisation of the deep foundation industry can be found in the EFFC/DFI Sustainability Guide for Foundation Contractors – Guide No.1 Carbon Reduction (EFFC/DFI, 2024).

As an example, it considers proposing the use of binder types with less impact than Ordinary Portland Cement, i.e. use of supplementary cementitious materials (additions) as a cement replacement in the mix design.

Also, through the improved understanding of tremie concrete behaviour and its performance and placement requirements, the application of recommendations in this Guide are provided to minimise imperfections in deep foundations. The production of quality deep foundations and good record-keeping without the need for remedial repairs or replacement foundations supports the principles of the Circular Economy for eliminating waste and circulating products and materials at their highest value suitable for their intended purpose and end of life reuse. Further discussion on the Circular Economy and Responsible Consumption and Production of deep foundations can be found in the EFFC/DFI Sustainability Guide for Foundation Contractors – Guide No.2 Circular Economy (EFFC/DFI, 2024).

The tremie process also impacts many wider areas of environmental sustainability. For example, embodied water in the concrete, as well as the treatment of the support fluid it displaces, will be addressed in EFFC/DFI Sustainability Guide – Guide No. 3 Water use (EFFC/DFI, 2024).

Section 6

Execution

6 / Execution

6.1 General

This section reviews techniques and methods used for pouring concrete by the tremie technique in deep foundations (bored piles, diaphragm walls and barrettes).

European, American and International Standards and Codes of Practice vary. The Guide therefore makes recommendations as to what is considered good practice.

This section does not cover "dry" pouring conditions where the concrete is usually allowed to free-fall over a certain height. European standard EN 1536 and ICE SPERW allow concreting in dry conditions if a check immediately before the placement proves that no water is standing at the base of the pile bore. The U.S. Department of Transportation FHWA GEC10 (2018), defines "dry as less than 75 mm [3 in] of water on the base of the bore, and an inflow not greater than 25 mm [1 in] in 5 minutes. In the case of greater inflow of water, it is recommended that the excavation is filled with water from an external source to overcome the inflow with positive fluid head within the excavation, and then to use the tremie technique for pouring concrete. The placement of concrete into an excavation with excessive inflow of water entails a risk of the incoming water mixing with the fresh concrete.

6.2 Prior to Concreting

It is essential that the base of the excavation is reasonably free of loose debris, which can be stirred up by the initial charge of concrete from the tremie and may accumulate in the interface layer. It is difficult to remove all debris from the base. Minor amounts of debris are normally acceptable.

Where there is a high reliance on base cleanliness, such as load bearing elements that rely heavily on end bearing capacity, it is important that debris at the pile or panel base is kept to a minimum. The benefits of additional time taken to clean the base should be balanced against any negative effects that this could cause (e.g increased build-up of filter cake).

Appropriate levels of base cleanliness should be discussed and agreed at the project design stage and verified accordingly on site. A range of methods for checking base cleanliness is available and some examples are provided in FHWA GEC10, and in ICE SPERW (2017).

It should be noted that the geometry of the excavation tool will dictate the shape of the base. With grabs and cutters, a curved profile is formed at the base. In such cases it is essential that the location of any base cleanliness checks is carefully considered and recorded. *Figure 14* shows the special situation of cutting into hard material using a trench cutter, where the base can only replicate the shape of the cutting wheels, including the over-cut zone in large panels with centre bites.

Bases of piles are cleaned using a cleaning bucket, submersible pump, air lift, or other proven system. Bases of diaphragm walls are normally cleaned using the excavation equipment or other proven system.

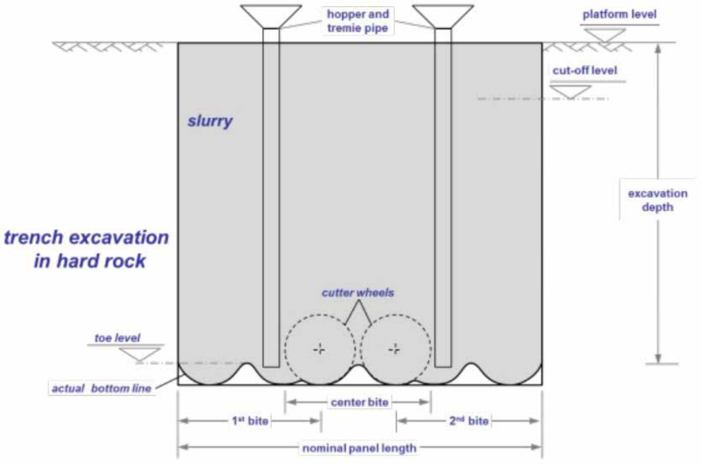
The EFFC/DFI Guide to Support Fluids for Deep Foundations discusses options and limitations to control the filter cake thickness by controlling the support fluid properties.

The support fluid should comply with the specified properties given in the EFFC/DFI Support Fluid Guide prior to insertion of the reinforcement cage and pouring of the concrete.

Before the insertion of the reinforcement cage (and commencement of pouring), it should be confirmed that the actual conditions are in accordance with the design and specifications e.g. excavation depth, nominal concrete cover (spacers) and reinforcement cage. Spacers should ensure the correct positioning of the cage in the excavation (or casing) and should be designed based on site specific conditions.

In multi bite diaphragm wall panels, the bottom level of each bite should be the same to within 0.5 m [2 ft] except in particular cases such as multi bite panels founded on inclined hard rock. Where the panel is stepped, the placement process must take this into account.

FIGURE 14 BASE PROFILE REFLECTING THE EXCAVATION TOOL GEOMETRY (EXAMPLE SHOWN USING A CUTTER)



The time elapsing between the final cleaning of the excavation and commencement of concreting should be kept as short as possible. Where elements such as stop-ends or reinforcement cages are to be inserted, cleaning should be carried out before insertion. The cleaning procedure, as well as the time between operations, should be established on the first panels. If delays occur, the support fluid quality should be rechecked and additional cleaning carried out if necessary.

Debris and particles may settle out of the support fluid and accumulate on top of the rising concrete surface in the interface layer which is discussed in more detail in the EFFC/DFI Support Fluid Guide. To allow for later removal of any unsound concrete above cut-off level, concrete is over-poured above the theoretical level resulting in sound concrete at cut-off level.

6.3 Tremie Equipment

Gravity tremie pipes should have a minimum internal diameter of 150 mm [6 in], or six times the maximum aggregate size, whichever is greater (EN 1536, FHWA GEC 10). A diameter of 250 mm [10 in] is commonly used. Pressurised tremie systems (pump lines) may be smaller than 150 mm [6 in]. ACI 336 recommends at least 200 mm [8 in] for gravity-fed tremie pipes and 100 mm [4 in] for pump lines.

Tremie pipes should be made from steel, as aluminium reacts with concrete.

Segmental pipes should be connected by a fully watertight structural connection. Typical sections have a length of 1 m to 5 m [3 ft to 15 ft]. Longer sections are generally preferred as this leads to fewer joints, but the order of the various lengths has to be considered according to the specific conditions (e.g. depth of excavation, hopper elevation, embedment at first pipe removal, and for the last loads at low hydrostatic pressure). In general, the pipes should be split at every joint each time they are used, and stored in a tremie frame, to allow proper cleaning. There have been examples of joints failing during tremie handling, so full visual checking is strongly recommended.

- Solid tremie pipes (without joints) may be used on shallow excavations where handling of the tremie permits.
- The hopper should have as large a volume as possible. The filling rate must allow for a continuous concrete supply to the tremie during the initial embedment of the tremie pipe.
- The pipes should be smooth clean and straight so that the frictional resistance to the concrete flow is minimised.

6.4 Tremie Spacing

Piles are normally circular and a single tremie pipe placed centrally within the bore is usually sufficient.

For diaphragm walls, codes specify various limits to the horizontal flow distance from 1.8 m to 2.5 m, [6 ft to 8 ft] with a maximum of 3 m [10 ft] (ICE SPERW, EN 1538, Z17). It is recommended that the distance is limited to 2 m [7 ft]. Longer travel distances of up to 3 m [10 ft] might be acceptable if the workability of the concrete is proven sufficient, in combination with clear spacing of reinforcement bars and concrete cover in excess of the minimum values. Full scale trials or numerical simulations (in particular by comparative studies) may assist in finding allowable values, see *Sections 7* and *9*.

The tremie pipes should be positioned as symmetrically as possible in plan to avoid uneven rises in concrete level e.g. central for a single tremie pipe and approximately ¼ of panel length from each end with 2 tremie pipes.

6.5 Initial Concrete Placement

Initiation of the concrete placement is one of the most critical steps in the entire placement process as the first load of concrete has to be separated from the support fluid.

Both wet and dry initial concrete pouring methods are described in various standards, guidelines and published technical papers (e.g. FHWA GEC10).

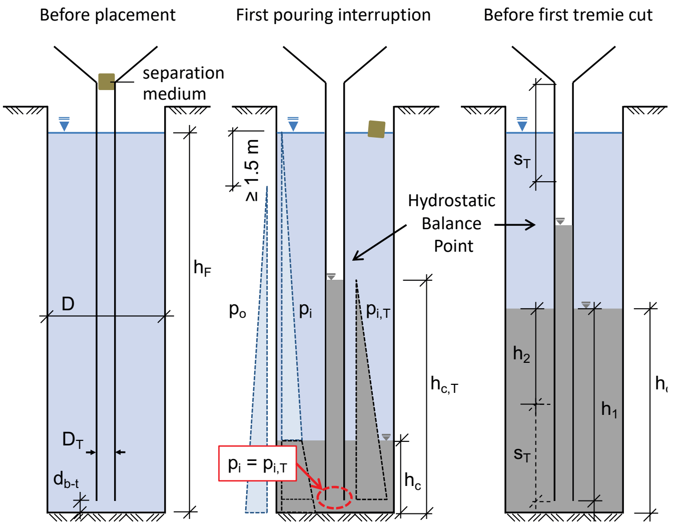
In the dry initial placement (often mistaken with "dry pour") method, the end of the tremie pipe is closed and the concrete only gets into contact with the support fluid once it flows out of the tremie pipe. A steel or plywood plate with a sealing ring is placed on the bottom of the tremie pipe which enables fluid to be kept out of the pipe during lowering to the base of the excavation. The concrete is then discharged directly into the dry tremie pipe, and the pipe lifted by 0.1 m to 0.2 m [4 to 8 in] to allow the concrete to flow into the excavation. For deeper pours, it can be difficult to prevent fluid entering the tremie pipe through the segmental joints and/or prevent the tremie pipe from floating.

With the wet initial placement method, a separation medium must be used as the tremie pipe is full of fluid. Examples for such "plugs" include vermiculite granules (possibly bundled in a sack), inflatable rubber balls, sponges and foam balls and cylinders. A steel plate is sometimes additionally used at the base of the hopper when the hopper is filled and the plate then lifted using a crane. The plug must prevent the initial charge of concrete from mixing with the fluid which would lead to segregation in the tremie. To start concreting, the tremie pipe should be lowered to the bottom of the excavation and then raised a short distance (no greater than the diameter of the tremie pipe) to initiate concrete flow and allow the plug to exit from the base of the tremie. ICE SPERW states that a sliding plug of vermiculate should have a length of two times the tremie diameter and that the tremie should not be lifted more than 0.2 m [8 in] from the base. For practical reasons the wet initial placement method is the preferred method.

Figure 15 shows the pressure conditions before and during the stages of the pour and highlights that before the first cut the tremie pipe must be sufficiently embedded. However, due to dynamic aspects of concrete flow, the actual concrete level in the tremie pipe, in particular at the interruption after the initial pour, might be lower than the hydrostatic balance point as indicated in *Figure 15*.

The required concrete level should be assessed for each specific site condition but in most circumstances a minimum of 5 m [15 ft] (6 m [18 ft] according to EN 1536 , and ACI 336) is required before the first split of the tremie. It is essential that a sufficient volume of concrete, which is defined as the quantity to fill the minimum height, is available on site before the pour is commenced.

FIGURE 15 PHASES IN THE TREMIE POUR SEQUENCE



Where:

h_F	Fluid level in excavation
D_T	Diameter of tremie pipe
D	Dimension (diameter or thickness) of excavation
d_{b-t}	Distance from bottom of excavation to tremie pipe outlet
h_c	Concrete level in excavation
$h_{c,T}$	Concrete level in tremie pipe (= hydrostatic balance point)
h_1/h_2	Embedment of tremie pipe before (1) / after (2) tremie pipe cut
s_T	Section length of tremie pipe section to cut, with: $h_2 \geq 3$ m [10ft]
p_o/p_i	Hydrostatic pressure outside (o) / inside (i) of excavation
$p_{i,T}$	Hydrostatic pressure inside the tremie pipe

6.6 Tremie Embedment

The tremie requires a minimum embedment into the concrete that has already been poured. European execution standards (EN 1536, EN 1538) specify a minimum embedment of 1.5 m to 3 m [5 ft to 10 ft], with higher values for larger excavations. In general, a minimum embedment of 3 m [10 ft] is well accepted in practice (and is required in accordance with ACI 336).

If temporary casing is being used during the tremie concrete pour, the removal of temporary casing sections should be considered with respect to maintaining minimum tremie embedment. Removal of temporary casing sections will cause the concrete level to drop as concrete fills the annulus left by the casing. Prior to removing a section of temporary casing, the tremie embedment depth should be adequate to maintain the minimum required embedment as the concrete level drops during casing removal.

Note: Where casings are removed by means of vibrators, special consideration should be given to the risk of dynamic segregation and suitability tests should cater for the required fresh concrete stability.

When two or more tremie pipes are used (see *Section 6.4*) the tremie bases have to be kept at the same level (except where the base is stepped which requires special initial measures).

To get the concrete to flow, the weight of the concrete within the tremie pipe must overcome:-

- The resistance outside the base of the tremie pipe (hydrostatic fluid pressure)
- The resistance of the concrete already poured
- The friction between the concrete and the inside face of the tremie pipe

Some authors refer to the 'hydrostatic balance point' where the gravity force within the tremie is in equilibrium with the resistance to flow (see *Figure 15*). Any concrete added above the hydrostatic balance point will cause the concrete to flow, and the higher the pouring rate the faster the flow out of the tremie outlet.

There are strong technical arguments to avoid excessive tremie embedment. Greater embedment leads to lower head pressure, loss of energy supply and slower concrete flow. Embedment ranging from 3 m [10 ft] minimum to 8 m [25 ft] maximum is recommended. At the end of the pour, i.e. close to the platform level, it is acceptable to reduce the minimum tremie embedment to 2 m [7 ft].

For small diameter bored piles the maximum embedment may need to be increased to avoid the need to split the tremie before an individual concrete truck load is fully discharged.

Note: The distance between the outside of the tremie pipe and, typically, the inside of the reinforcement cage should be large enough to prevent from the risk of lifting the cage with the pipe due to friction. Relevant standards may give provisions, e.g. NZGS Piling Guideline.

It is mandatory to measure the depth to the concrete at tremie positions after each load of concrete has been poured, which is often performed using a weighted tape. Where two (or more) tremie pipes are used in one panel it is essential to minimise the difference in concrete levels and discharge into both tremie pipes at the same time.

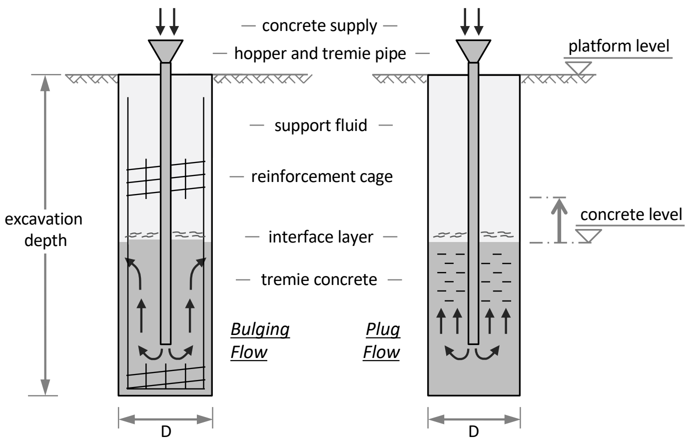
Concrete should flow freely from the tremie without the need of surging (rapid raising and lowering of the tremie). The need to surge the tremie in order to maintain flow is generally an indication of loss of workability. This can affect the concrete flow pattern and may risk mixing of support fluid and contaminated material on top of the concrete leading to debris entrapment.

A suitable methodology for re-embedding the tremie pipe after accidental removal above the level of the concrete, or in the case of interruption of concrete delivery, should be detailed in the submittals and/or agreed upon in advance of the commencement of execution of works (see also EN 1536, Clause 8.4.8 , or NZGS Piling Guideline).

6.7 Concrete Flow Mechanisms

Results from field trials (Böhle and Pulsfort, 2014), and numerical modelling simulations (see *Section 9*) have confirmed that there are two basic types of flow: 'bulging' and 'plug'. These are shown schematically in *Figure 16*.

FIGURE 16 SCHEMATIC OF BULGING AND PLUG FLOW



Based on a limited amount of field test data and numerical modelling simulations, bulging flow is believed to be the most common flow type in deep tremie pours. The fresh concrete, after leaving the tremie pipe outlet and turning upwards, is understood to establish a laminar flow for a distinctive distance in a confined centre area of the excavation, following the path of least resistance to flow (around the tremie pipe), and then to spread outwards at the top of the concrete. The older concrete is displaced upwards and sidewards and is then "consumed" within the outer circumference of the excavation, where relatively high resistance to flow prevails. Consequently, bulging flow is common especially in structural deep foundations where a reinforcement cage represents a major obstruction to vertical flow. A rough excavation face will also resist the concrete flow and contribute to bulging flow.

Plug flow exhibits a plug of concrete on top of the concrete column inside the excavation (or well inside the cage) and above the tremie pipe outlet, which is raised upwards by a fluid pressure induced underneath by "pumping" fresh tremie concrete which displaces the older concrete to the top. It is assumed that the fresh concrete is not mixing into the plug. An extreme case of plug flow would imply that the plug concrete is not sheared i.e. that it is internally at rest and prone to thixotropic effects. Plug flow is considered more probable in cases where a very low friction at the outside is prevalent (e.g. no cage and a smooth excavation surface) or for the inner section of a wide excavation, the latter which would result in combined bulging and plug flow.

There are multiple interdependent factors determining which type (or combination of types) of flow actually occurs. The flow in an individual deep foundation element can also vary during a single pour e.g. due to time dependent rheology of the concrete, local steel congestions or changes in the effective hydrostatic conditions. To better understand these complex interactions and isolate the most sensitive parameters, numerical modelling can be used (see *Section 9*).

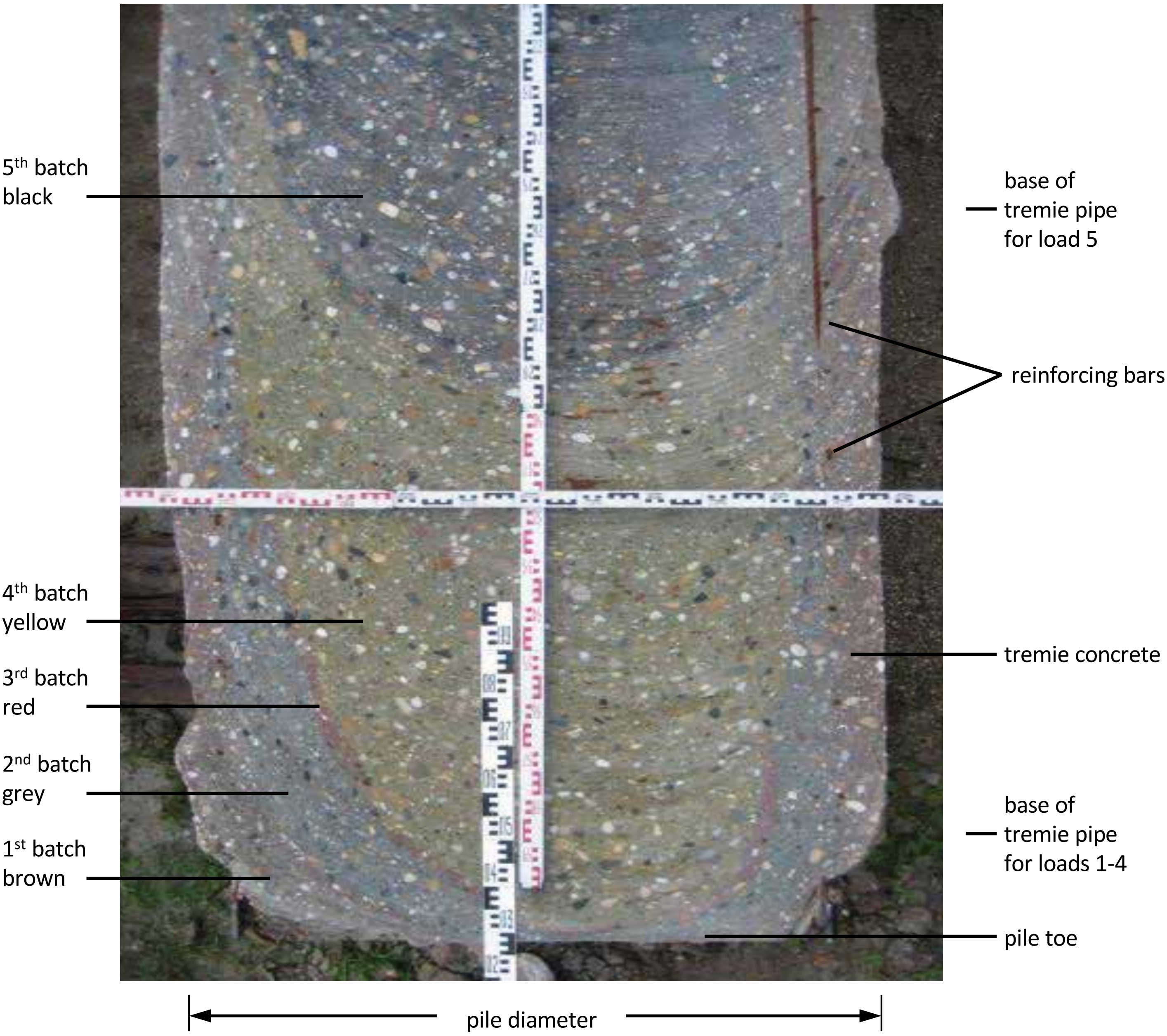
Concrete flow patterns have occasionally been investigated in the field but are still not fully understood. Further research is on-going, where the concrete flow patterns from the tremie pipe are numerically modelled, including the interface layer, using fluid dynamics programs or simulations (Böhle and Pulsfort, 2014).

Figure 17 shows a cut longitudinal cross section of a bored pile which had been cast using dyed concrete in order to investigate the flow pattern under specific conditions. The visible flow pattern shows earlier poured concrete at the outside (especially in the cover zone) and later poured concrete in the centre. The yellow and black dyed concrete batches were poured from two different outflow levels before and after splitting the tremie pipe.

The associated flow mechanism is understood to be systematic for a multi-stage pouring process where the tremie pipe is lifted in defined steps and displaces older concrete to the top and to the sides, indicative of the bulging flow mechanism.

Note: the red dyed concrete from the 3rd batch is only visible as a thin layer between the 2nd (grey) and 4th (yellow) batch. This might indicate a change in the flow pattern, e.g. by a distinctive variation in rheology, or forced by the boundary conditions (within the excavation)

FIGURE 17 CROSS SECTION OF A BORED PILE CAST WITH DIFFERENTLY DYED LOADS OF TREMIE CONCRETE (BÖHLE AND PULSFORT, 2014), INDICATING BULGING FLOW



The dominant rheological property affecting the concrete flow pattern is the yield stress (indicated by the slump-flow). The viscosity (indicated by the slump-flow velocity) can have an effect on the overall time required for a pour (slower flow of concrete) and may affect the demand for workability retention, which should be reduced wherever possible. The viscosity also directly effects the resistance to flow of the (horizontal) concrete through windows in the reinforcement cage.

Where yield stress and viscosity increase with time, it may be necessary to adapt execution techniques during the pour e.g reducing the tremie embedment depth towards the end of the pour.

6.8 Flow around Reinforcement and Box-Outs

As set out in *Section 2*, special consideration has to be given by the Structural Designer for any restriction to concrete flow. Any obstruction is a resistance to flow and will decrease the potential of the concrete used to properly flow around and embed a reinforcement bar or box-out. As the actual flow is a function of energy at the point of resistance, congestion is more critical at greater travel distances from the tremie pipe outlet and at higher elevations where the concrete head pressure is lower.

Detailing of the reinforcement cage, box-outs etc. has to comply with the codes (see *Appendix E*). In addition, numerical modelling may be used to assess the sensitivity to changes in detailing and determine the least disruptive configurations.

Spacer blocks and other embedded items should be profiled to facilitate the flow of concrete.

6.9 Concreting Records

The depth of the concrete level at each tremie position and the embedded length of the tremie pipe recorded should be measured and recorded after the discharge of each load of concrete. The concrete levels are important not just to check tremie embedment but also to determine the level of the concrete where the cut-off is below platform level, especially if there is a significant amount of interface material. It is also possible to measure the concrete depth inside and outside the reinforcement cage to give an indication of the type of flow.

There are a number of methods commonly used to determine the level of concrete surface during the concreting process. A weighted tape is often used because it is simple, reliable, and practical. Other types of weight are used. All rely on the weight successfully penetrating any interface layer and then coming to rest on top of the concrete. Where the properties of the interface layer and the concrete are similar, it will be difficult to accurately determine the level of the top of the concrete. There is no known simple method currently available which can determine the actual depth to the top of the concrete with a high degree of accuracy. Consistent accuracy may be obtained by using the same equipment and a single operator, but the values are still subjective.

Note: The Field Research Study currently being undertaken by the EFFC/DFI Support Fluids Working Group includes a comparative study using different methods dispersed across the surface area of the foundation elements during the concreting process. Different concrete levels have been measured at different positions (and edge of the element). These can provide useful information on the flow pattern of the concrete and assist in identifying any unusual distribution of the concrete flow.

The depths measured, volumes poured, tremie lengths and casing lengths should be plotted immediately on a graph during the pouring operation and be compared with the theoretical values, considering the effects of excavation over-break. An example of such a graph is given in both EN 1538 and FHWA GEC10.

Such a comparison can help identify areas where over-break may have occurred or where concrete may be filling voids. Under-break is rare and under-consumption of concrete might indicate an issue such as instability, collapse, or mixing of support fluid, debris or soil with concrete. These measurements can identify an unusual condition in an excavation where more investigation may be warranted.

Section 7

Full-Scale Trials

7 / Full-Scale Trials

An effective way to obtain information on any deep foundation element is to install one or more full-scale test elements. These should ideally be constructed using the same installation technique, equipment and materials as proposed for the permanent works. Problems identified in full-scale trials can then be addressed before the permanent works are constructed. They also provide opportunities for refining aspects of the construction process and developing compliance parameters.

The extent and scope of the trial works should be proportionate to the project size, complexity and risks. The components to be tested should be selected from a review of:-

- The design and detailing
- The fresh concrete performance
- The Constructor's placement methods, overall experience and capability
- The experience in the given ground conditions

This may require temporary works to enable excavation to expose constructed elements to a significant depth. The scope of the full-scale trial works should be prepared to also include methods to inspect and investigate for imperfections and their evaluation e.g. with coring, non-destructive testing, photography and laboratory testing.

In practice, such trials are best carried out by the appointed Constructor after mobilisation to site but prior to commencement of the permanent works. The time and cost of the trial must be recognised by the Client at an early stage, and specified in detail in the tender documents.

When budget and/or time schedule constraints do not allow for such full-scale trials, it is recommended to at least perform on-site suitability testing on site, in addition to the suitability testing typically performed in the Concrete Producer's laboratory.

Section 8

Quality Control of Completed Works

8.1 General

It is essential that the Constructor complies with relevant standards for quality assurance and control, and that the production process is supervised and undertaken by competent persons with suitable training, qualifications and experience.

Concrete placed in bored piles, diaphragm walls and barrettes is normally cast against the face of an open excavation and the placement process is not visible from the surface. Some imperfections of the hardened concrete of the deep foundation element are possible even though good practice construction methods were applied by the Constructor. Quality control requirements for the completed works should therefore make allowance for acceptance of some imperfections where these are not significant with regard to the structural performance and durability of the completed works. To support efficient and consistent inspection and acceptance, criteria for acceptance of foundations (including foundations with imperfections) should be clearly specified in work procedures and inspection and test requirements.

Acceptance criteria may be based on past experience or through construction trials undertaken prior to the commencement of the main works. It is better to spend time and effort on trials before the works commence, when production problems can be prevented, rather than specifying detailed and expensive quality control tests after completion, when problems can only be mitigated, typically at great expense. Another option is to expose and test a limited sample of piles or wall panels after the construction of the first elements and this can form part of the QA/QC procedures allowing any required corrective action(s) to be implemented at an early stage.

8.2 Post-Construction Testing Methods

A number of integrity testing methods, both destructive and non-destructive, are commonly available to provide information regarding the geometry and the quality of the completed pile or wall. An overview of commonly available methods is given in *Appendix C*.

Non-destructive test methods require specialist knowledge and experience to interpret results and findings correctly. Imperfections in deep foundations generally fall into one of three categories:-

- Inclusions
- Bleed Channels
- Mattressing (may also be referred to as ‘shadowing’ or ‘quilting’)

A further description of each category of imperfection, together with examples, is given in *Appendix D*.

There are other imperfections which are either very infrequent or not related to the tremie concreting process e.g. thermal cracking, and inclusions from groundwater flow (including artesian water pressures). These are beyond the scope of this Guide.

Common to all integrity test methods is the need for thorough, complete records of installation. Such records are essential to allow proper interpretation of integrity test results and to distinguish between anomalies (unusual test data) and actual imperfections in completed works. If imperfections are assessed to represent defects, with the potential of making the deep foundation unfit for purpose, and if these are frequent, it can be possible to postulate an imperfection formation mechanism, which if detected early enough will enable changes to detailing, materials or construction processes to avoid further occurrences.

Imperfections can be caused by inappropriate detailing, by concrete that does not have appropriate flow properties or the adequate stability for the detailing and placement procedure in place, or by poor workmanship. Applying the recommendations of this Guide, especially by following the mutual approach of interaction between all parties involved, should help to minimise imperfections.

Section 9

Numerical Modelling of Concrete Flow

9 / Numerical Modelling of Concrete Flow

9.1 Introduction

Numerical modelling can be an effective tool to understand the importance of individual factors (as set out in *Table F.1*) affecting the behaviour of fresh concrete alongside assessing the sensitivity of these factors to changes. When validated by physical observations, numerical modelling serves as a valuable tool for the development of practical recommendations related to tremie concrete properties as well as design and construction practices.

9.2 Studies undertaken

The Numerical Modelling Subgroup comprises both academics and industry professionals who have produced and reviewed current publications relating to numerical modelling of tremie concrete.

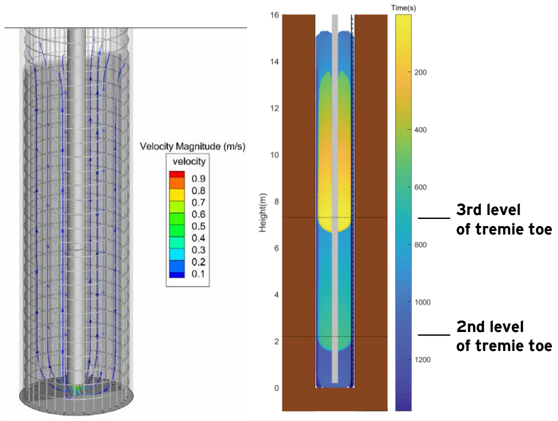
Appendix G provides examples where practical recommendations may be drawn from these numerical studies, many of which focus on the bulk flow behaviour of tremie concrete.

In summary, practical recommendations drawn from published studies highlight:

- Flow patterns are likely related to the degree of restriction imposed on the fresh concrete by boundary conditions of the foundation.
- The need for a deeper understanding and, practical test of concrete thixotropy.
- Exposed reinforcement imperfections could be related to concrete rheology.
- The importance of maintaining consistent concrete properties throughout the pour.

Figure 18 illustrates an example of a 1.5 m [5 ft] diameter bored pile with a depth of 16 m [52 ft] and a reinforcement cage, with concrete pour simulating staged lifting of the tremie pipe.

FIGURE 18 **EXAMPLE OF A NUMERICAL MODEL, CONCRETE FLOW VELOCITY STREAMLINES (LEFT), FLOW BEHAVIOUR OF CONCRETE DURING A MULTI-SEQUENCE POUR**



A review of the model studies has resulted in a number of important conclusions and these are discussed in *Table F.1*, and further details on Numerical Modelling studies undertaken are given in *Appendix G*.

9.3 Limitations

Processing time for simulations is dependent on the degree of detail of the model itself and can extend, with present computer technology, up to a number of weeks for each individual numerical model simulation. Accurately defining the physical shape and size of the reinforcement cage greatly increases computation time. The option to replace the cage with a porous membrane may give good correlation (for bulk-flow simulation) but involves far less computation time (Roussel and Gram, 2014).

It is important to balance the complexity of the model with the envisaged sensitivity to the effect of change in parameters (based on experience from earlier simulations) in order to reduce the computation time and thereby allow more simulations to be carried out.

Numerical simulation is a powerful tool to solve the governing partial differential equations derived from the physical model. Hence the significance of numerical simulation is limited to the capacity of the underlying physical model (e.g. the Bingham fluid model).

Further details on limitations of numerical modelling and recommendations for validation when used, are given in *Appendix G*.

Appendix A

Test Methods to Characterise Fresh Concrete

The practical tests described in this Appendix can be used to determine:-

- Workability, represented by yield stress and viscosity
- Workability retention, including also thixotropy
- Stability

Note: The tests should be carried out in strict accordance with the method descriptions given in this Appendix. Any deviations must be clearly documented.

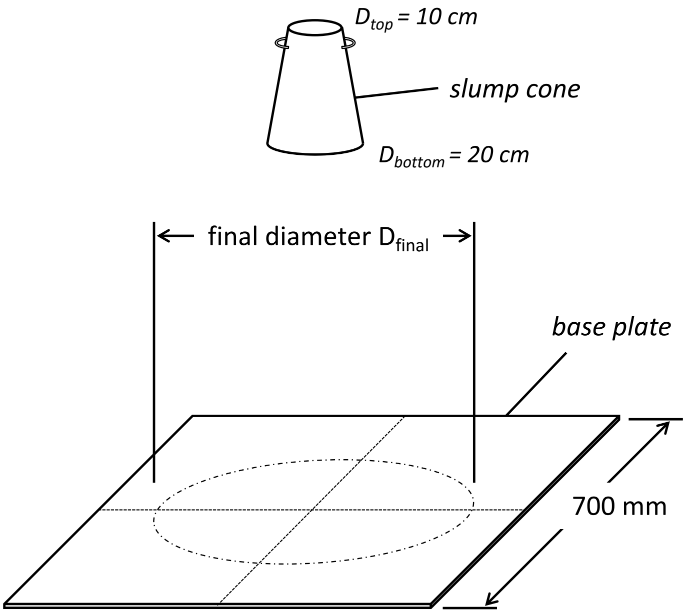
A.1.1 Slump-Flow Test in accordance with (EN 12350-8 and ASTM C1611)

PRINCIPLE: The slump flow is a measure of the workability, and can be directly related to the yield stress.
PROCEDURE: The test is based on the slump flow test described in EN 12350-8 and ASTM C1611. The 300 mm [12 in] high hollow truncated cone and the base plate are dampened and the cone is placed on the horizontal base plate, see *Figure A.1*, and the fresh concrete is filled in the cone. When the cone is raised the concrete will slump and flow. The final diameter of the concrete is measured (slump-flow in mm).
The test sample obtained should be re-mixed before carrying out the test, using a remixing container of at least 10 l [2.6 GAL] volume, and a square mouthed scoop.
The test apparatus, comprising of a truncated cone and a flat steel base plate as shown in *Figure A.1*, shall conform to EN 12350-8 or ASTM C1611. The "slump cone" is the same as used for the slump test, and the base plate shall accordingly be of non-absorbent material not readily attacked by cement paste so that the concrete flow is not restricted.
It is important to dampen the clean plate and mould before filling the cone with concrete.
Provided that the workability is sufficient to self-compact, the concrete does not need to be compacted in layers, and the concrete can be filled in one operation without any agitation or mechanical compaction. Heap the concrete above the mould to keep an excess before striking off the surface of the concrete by means of a sawing and rolling motion of a rod. Spilled concrete must be removed from the base plate before raising the mould carefully and by a steady vertical upward lift (within 30 s of filling the mould) taking between 1 s and 3 s.
After the flow of concrete has ceased, the diameter of the flow spread shall be measured two times at right angles to the nearest 10 mm [0.4 in] and recorded as the average diameter. If both single values differ by more than 50 mm [2 in] a new sample should be taken and tested.
REMARKS: This test can be combined with the Slump Flow Velocity Test (A1.2) and the Visual Stability Index Test (A.1.3).

A.1.2 Slump-Flow Velocity Test

PRINCIPLE: The slump-flow velocity is a measure of the workability, and can be directly related to the viscosity.
PROCEDURE: The test set-up is the same as with slump-flow, see *A.1.1* and *Figure A.1*. In addition, a stop watch is needed capable of measuring to 0.1 s.
When the cone is raised the concrete will slump and flow, and the time T_{final} [s] taken for the concrete to spread to the final diameter D_{final} [mm] is measured.
The final diameter is equal to the slump-flow (see *A.1.1*). i.e. the average value of the two diameters measured at a right angle and recorded to the nearest 10 mm [½ in].
The stop watch shall be started immediately when the cone leaves the base plate and taken to the nearest 1 s in which the concrete flow is considered to have stopped (when the horizontal movement is less than 1 mm/s).
The travel distance (D_{final} - 200)/2 [mm] divided by the time taken t_{final} [s] is the slump-flow velocity [mm/s]. (for US use (D_{final} - 8)/2 [in] to derive [in/s].
REMARKS: This test can be combined with the Slump-Flow Test (*A.1.1*) and the Visual Stability Index Test (*A.1.3*).
The original test specifies a T_{500} flow time as the time the concrete needs to spread to a diameter of 500 mm [20 in].
Since tremie concrete may not necessarily spread that far, this specific measure is deemed inapplicable for tremie concrete.

FIGURE A.1 TEST EQUIPMENT FOR COMBINED SLUMP-FLOW, SLUMP-FLOW VELOCITY AND VSI TEST



A.1.3 Visual Stability Index Test (ASTM C1611)

PRINCIPLE: The visual stability index (VSI) is the result of a visual assessment and classifies the segregation resistance.
PROCEDURE: Same as with slump-flow, see *A.1.1*, followed by visual inspection using the criteria listed in *Table A.1*.
REMARKS: This test can only indicate obvious segregation tendencies and may not be sufficient to detect sensitive concrete mixes. For more reliable measurement, and in cases of doubt, the static segregation test (*A.8*) or the sieve segregation test (*A.9*) should be used.

TABLE A.1 VISUAL STABILITY INDEX VSI CLASSES (ACCORDING TO ASTM C1611)

VSI VALUE	CRITERIA
0 = Highly Stable	No evidence of segregation or bleeding
1 = Stable	No evidence of segregation and slight bleeding observed as a sheen on the concrete mass
2 = Unstable	A slight mortar halo ≤ 10 mm [½ in] and/or aggregate pile in the center of the concrete mass
3 = Highly Unstable	Clearly segregating by evidence of a large mortar halo > 10 mm [½ in] and/or a large aggregate pile in the centre of the concrete mass

FIGURE A.2 EXAMPLES OF VISUAL STABILITY INDEX CLASSES

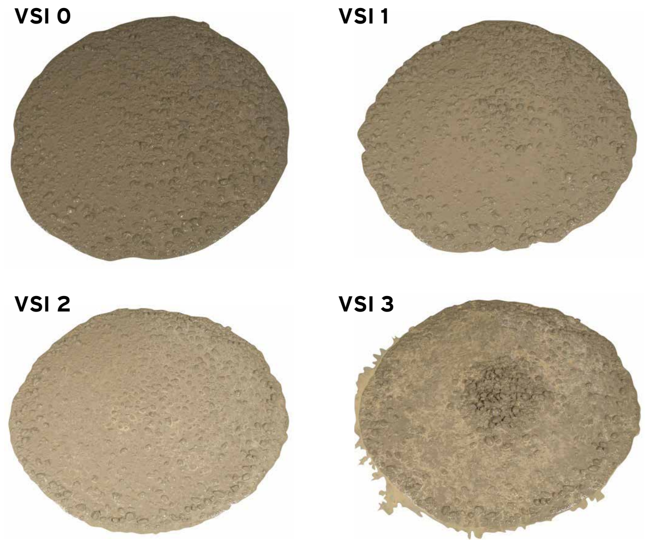

VSI 0
VSI 1
VSI 2
VSI 3

Photo courtesy of Master Builders Solutions Corporation

A.2 Flow Time

PRINCIPLE: The outflow time of the concrete from the inverted cone is a measure of the workability, and can be related to the viscosity.
PROCEDURE: The test is based on French National Standard NF P18-469, using the same equipment as for the slump-flow test according to A.1, plus a stop watch. The cone is placed upside down (inverted) on the flat steel base plate, with the 100 mm [4 in] wide opening at the bottom. The concrete is filled into the cone in one operation and compacted 25 times with a rod. After striking off the surface and waiting for 30 s the cone is lifted vertically by approximately 40 cm [16 in] within 2 to 4 seconds. The outflow time of the concrete is recorded until the cone is empty. Time is recorded to the nearest 0.1 s.
REMARKS: If this test is envisaged to be used for conformity or identity testing, a target value should be determined and agreed within the suitability testing.
This test has been shown to give reliable information for tremie concrete mixes to detect low, medium and high viscosity.
Without a detailed specification, a minimum of 2 seconds and a maximum of 7 seconds might apply as the recommended range for identity testing.

A.3 Workability Retention Test

PRINCIPLE: The workability retention test measures the time span over which the concrete retains a specified slump-flow.
PROCEDURE: According to EN 12350-1, repeat the slump-flow tests (A1.1) at discrete intervals up to the assessed total pouring time needed for the specific element.
Batch fresh concrete (for field trials preferably 3 m^3 [4 cy] but a minimum of 1m^3 [1.3 cy]).
Store the sample (or sufficient sub-samples) in sealable cylindrical containers made from non-absorbent material not readily attacked by cement paste, for receiving and storing increments of concrete. The ratio of height to diameter shall be in the range 0.7 to 1.3 and of sufficient size to fully retain the sample.
The quantity of the concrete sampled shall be not less than 1.5 times the quantity estimated for the tests and sufficient to fill the sealed container to within 25 mm [1 in] to 50 mm [2 in] of the cover.
Where the sample is intended to be used to measure slump retention at a specified time, the concrete from the sealed container should be emptied onto the remixing container or tray and remixed using a shovel or scoop before carrying out the test.
Perform slump-flow tests every 1 hour (2 h for workability retention specified for more than 4 h).
REMARKS: To check a concrete mix for thixotropic tendency, fill two slump cones with fresh concrete, and perform one slump-flow test immediately. After a resting period of 15 minutes, perform the second slump-flow test. If the difference in values is greater than 30 mm [1 ¼ in] the test should be repeated. Preliminary findings from the Research and Development Project indicate that thixotropy is significant in cases where the slump-flow after 15 minutes of rest is 50 mm [2 in] (or more) below the initial value.

A.4 Bleed Rate Test (ASTM C232 and prEN12350-13)

PRINCIPLE: The amount of water on the surface of concrete in a container is a measure of bleed, see *Figure A.6*.

PROCEDURE: Concrete is inserted to a height of 250 mm [10 in] into a cylindrical container of inside diameter 250 mm [10 in] and inside height of around 300 mm [12 in]. The segregation of water at the surface is measured every 30 minutes until a constant bleeding rate can be established or until the bleeding stops (as the concrete sets), taking a minimum of four measurements.

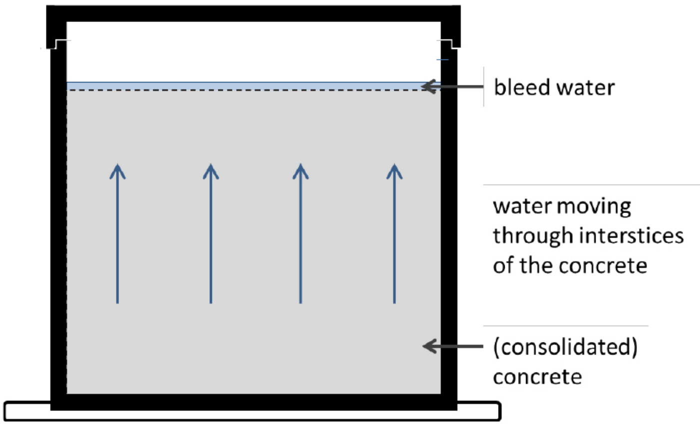
REMARKS: The time to commencement of bleeding and the following constant bleed rate (see *Figure 8* in *Section 3.3)* are essential to characterise the bleeding potential. Following commencement of bleeding an average bleeding rate within the relevant 2 hours of less than 0.1 ml/min [0.003 oz/min] is considered acceptable. According to prEN 12350-13 the relevant 2 hours with a theoretically constant bleeding rate start when the second non-zero value of bleed water on the surface is measured. The bleeding rate, B_R, expressed to the nearest 0.01 ml/min, is evaluated during the first bleeding phase. It corresponds to the average rate of bleeding observed over four consecutive measurements.

Thus, if V_i is the first collected sample greater than or equal to 0.5 ml, B_R is calculated using the following equation:

$$B_R = \frac{B_R = V_{i+1} + V_{i+2} + V_{i+3} + V_{i+4}}{t_{i+4} - t_i} = \frac{V_{ci+4} + V_{ci}}{t_{i+4} - t_i}$$

where V_{ci} is the volume of water accumulated up to time t_i.

FIGURE A.3 SCHEMATIC SET-UP TO DETERMINE BLEED DUE TO GRAVITY



A.5 Filtration Test

A.5.1 Bauer Filtration Test

PRINCIPLE: The test simulates the water retention ability of fresh concrete under pressure and determines the filter loss through a filter, as shown in *Figure A.6*.

PROCEDURE: A cylindrical container is filled with 1.5 litres [0.4 GAL] of fresh concrete and pressurized with compressed air at 5 bar [73 psi] for 5 minutes. The water which separates from the bulk concrete through a filter paper is collected at the bottom of the container in a cylinder. The recorded filter loss is a measure of the filter stability of the concrete.

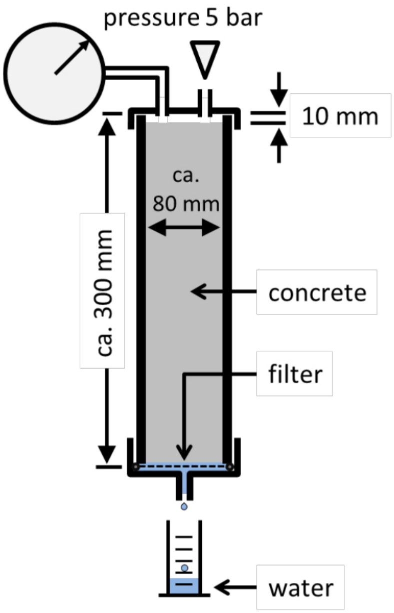
REMARKS: The maximum aggregate size should be limited to 20 mm. Use Special Hardened Filter Paper API of 90 mm [3.54 in] diameter (Fann® no 206051).

According to an acceptance criterion of 15 l/m^3 (from Z17, CIA), for tremie concrete in deep foundations (>15 m [50 ft] depth), the corresponding test value for the 1.5 l [0.4 GAL] sample is approx. 22 ml [0.7 oz].

The measured filter cake thickness and its consistency also give an indication of the concrete's robustness against loss of workability. A soft, flexible cake is preferable to a hard cake.

An alternative test method to determine the filtration loss is the "Austrian" Concrete Filter Press Test, see *A.5.3*.

FIGURE A.4 TEST ARRANGEMENT TO DETERMINE WATER LOSS FROM PRESSURIZED FRESH CONCRETE (BAUER)



A.5.2 Pressure Filtration Test (prEN 12350-13)

PRINCIPLE: The test simulates the water retention ability of fresh concrete under pressure and determines the filter loss through a filter, as shown in *Figure A.7* using the standard equipment for drilling fluids in accordance with *API RP 13B-1* and *EN ISO 10414-1*.

PROCEDURE: A cylindrical container (approximately 0.4 l [0.105 gal] is filled with a known mass of fresh concrete and pressurized with compressed air at 1 bar [14.5 psi] for 3 minutes and 30 s after an initial time of 15 s. The mass of the container is measured before and after filling. The mass of water which separates from the bulk concrete through a filter paper is collected at the bottom of the container in a cylinder. The result, acc. to the referenced standard named "*pressure bleed*" P_{Bn}, is expressed as a maximum consolidation (mm/m) by calculating the ratio between volume of water filtrated and the volume of the concrete sample, using the following equation:

$$PB_n = V_{filtered} / V_{concrete}$$

where

$$V_{concrete} = (m_{2p} - m_{1p}) / D(p)$$

m_{1p}	in [g]:	mass of the filtration cell (g)
m_{2p}	in [g]:	mass of the sample and filtration of cell (g) at the beginning of the test
$V_{filtered}$	in [ml]	
$V_{concrete}$	in [l]	
$D(p)$	in [g/l]:	density of fresh concrete, with a default value of 2350 g/l

REMARKS: The maximum aggregate size should be limited to 20 mm. Use Special Hardened Filter Paper API of 90 mm [3.54 in] diameter (Fann® no 206051).
A maximum value of 11 mm/m is correlated to a Bauer filtration value of 19 ml.

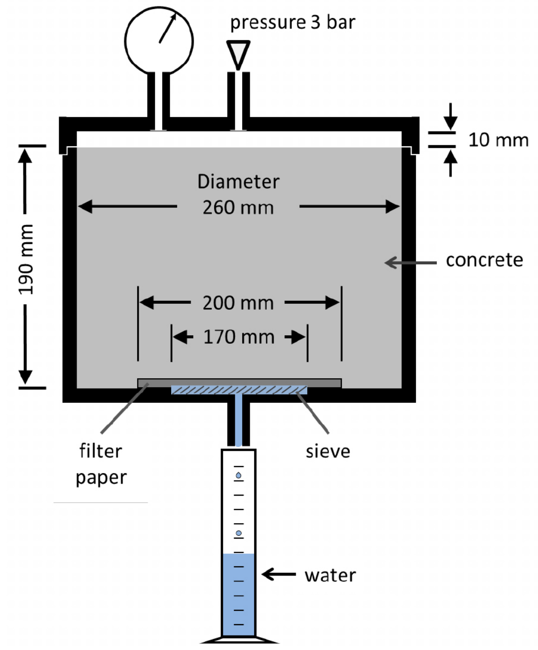
A.5.3 Concrete Filter Press Test (Austrian Guideline on Soft Concrete)

PRINCIPLE: The test simulates the water retention ability of fresh concrete under hydrostatic pressure and determines the filter loss through a filter, see *Figure A.8*.

PROCEDURE: A cylindrical container is filled with 10l [2.5 GAL] of fresh concrete and pressurized with compressed air (3 bar [44 psi]). The water that separates from the bulk concrete through a filter paper is collected at the bottom of the container in a cylinder. The recorded filter loss is a measure for the filtration stability of the concrete.

REMARKS: Industry internal tests indicate a correlation between this 'Austrian' concrete filter press test and the Bauer filtration test which is $V_{loss\text{-}15,ÖVBB}$ [l/m^3] / $V_{loss,BAUER}$ [l/m^3] = 1.8 (approx. 2), so that for the Concrete Filter Press Test approximately a filtration loss of 25 l/m^3 can be used as equivalent to 22 ml [0.7 oz] filtration loss from the Bauer Filtration Test.
In the Austrian Guideline on Soft Concrete a stability class FW20 is defined for tremie concrete where depth exceeds 15m [50ft]. The filtration loss no greater than 20 l/m^3 [4 GAL/cy] is recommended for suitability testing and 15 minutes filtration time (the according test value for the 10-l sample is 200 ml [6.8 oz]). An additional criterion a 40l/m^3 [8 GAL/cy] maximum loss can be specified for 60 minutes filtration time. For identity testing a 25 l/m^3 [5 GAL/cy] filtration loss is allowed at 15 minutes filtration time for the FW20 stability class.

FIGURE A.5 PRINCIPAL SET-UP TO DETERMINE WATER FILTRATED FROM PRESSURIZED FRESH CONCRETE (ACCORDING TO MERKBLATT "*WEICHE BETONE*")



A.6 Slump Test (EN 12350-2, ASTM C143)

PRINCIPLE: The slump of the concrete gives a measure of the workability.
PROCEDURE: The fresh concrete is filled and compacted in a mould that consists of a 30 cm [12 in] high hollow truncated cone, see *Figure A.1*. When the cone is raised the concrete will slump and the vertical distance the concrete has slumped is measured.
REMARKS: A serious lack of stability can potentially be detected visually.

Note 1: For the range of slump-flow 400-550 mm [16-22 in], Kraenkel and Gehlen (2018) found the equivalent range of slump to be 220-270 mm [9-11 in]. However, if the slump is envisaged for use in identity testing it is necessary to establish a correlation for the specific concrete mix during the suitability testing.
Note 2: Given the specified tolerance of 30 mm [1 in] for the slump test, this test is not considered appropriate for use with highly flowable tremie concrete. Further, EN206:2014 states, in Appendix L, that due to the lack of sensitivity of the test method, it is recommended to use the slump test only for $D_{slump} \leq$ *210 mm [8 in]. Consequently, this test should only be applied if the necessary workability can be specified by a target value of no greater than 210 mm [8 in].*

A.7 Flow-Table Test (EN 12350-5)

PRINCIPLE: The spread of the concrete gives a measure of the workability.
PROCEDURE: The fresh concrete is filled and compacted in a mould which consists of a 20 cm [8 in] high hollow truncated cone. After raising the cone the plate is lifted and dropped 15 times which leads to the final spread which is measured.
REMARKS: A serious lack of stability can potentially be detected visually. Due to the impacts from dropping it may be possible to detect a tendency for dynamic segregation.

Note 1: For the range of slump-flow 400-550 mm [16-22 in], Kraenkel and Gehlen (2018) found the equivalent range of spread from the flow table test to be 560-640 mm [22-25 in]. However, if the flow table test is envisaged for use in identity testing it is necessary to establish a correlation for the specific concrete during the suitability testing.
Note 2: Compared with the slump-flow test the flow table test has a lower sensitivity, and also uses dynamic impacts which may be more appropriate for dynamic placing (e.g. for concrete being vibrated). If the flow table test is used for identity testing, a tolerance of 40 mm [1.5 in] must be considered as stated in EN 206:2014, Appendix L.
Note 3: The initial spread (before the 15 hits) was found to be in the range 380-500 mm [15-20 in]. These values are lower and less selective than those from the slump-flow test as the energy supply is less with the lower cone (200 mm [8 in] for the flow table and 300 mm [12 in] for the slump-flow test).

A.8 Static Segregation Test

A.8.1 Static Segregation Test (or Washout Test) (ASTM C1610 and German DAfStb Guideline on SCC)

PRINCIPLE: The test evaluates static segregation by variation of coarse aggregate distribution over height.
PROCEDURE: A hollow column of 3 connected cylinders is filled and compacted with fresh concrete, see *Figure A.5* (the original standard and guideline allow no compaction or vibration, for SCC mixes). After a standard period, e.g. 2 hours, the proportion of coarse aggregate in the top and bottom cylinders is determined by washing and sieving. The difference in coarse aggregate is a measure of segregation.
REMARKS: The test was developed for self-compacting concrete (SCC) with intentionally low yield stress, where segregation of aggregates is controlled by viscosity and is therefore time dependent.
Depending on the workability time, also for tremie concrete, an adapted standing time might be more appropriate.
If the full setting time shall be taken into account the Hardened Visual Stability Index (HVSI) Test can be used, see *A.8.2*.

FIGURE A.6 ARRANGEMENT FOR STATIC SEGREGATION TEST IN ACCORDANCE WITH ASTM C1610

A.8.2 Hardened Visual Stability Index (HVSI) Test in accordance with AASHTO R81

PRINCIPLE: The test evaluates static segregation by visual assessment or examination of aggregate distribution in a hardened test specimen sawn in two.

PROCEDURE: A standard cylinder mould is filled with concrete, without compaction or vibration, and allowed to harden undisturbed. Once strong enough the specimen is sawn in two, axially, and the aggregate distribution compared with standard descriptions and photographs to determine the HVSI class, see *Table A.2*.

REMARKS: The test was developed for self-compacting concrete but is likely to be equally applicable to tremie concrete. It has the advantages of taking the full setting time into account, and not needing specialist equipment other than a concrete saw. The curing time for the concrete specimen to be strong enough to saw should allow for a minimum compressive strength of 6 MPa [900 psi], and should be 24 h at least.

TABLE A.2 CLASSIFICATION FOR THE HARDENED VISUAL STABILITY INDEX (HVSI) TEST

HVSI	CLASSIFICATION	DESCRIPTION
0	stable	No mortar layer at the top of the cut plane and/or no variance in size and percent area of coarse aggregate distribution from top to bottom
1	stable	Slight mortar layer, less than or equal to 6 mm [$^1/_4$ in] tall, at the top of the cut plane and/or slight variance in size and percent area of coarse aggregate distribution from top to bottom
2	unstable	Mortar layer, less than or equal to 25 mm [1 in] and greater than 6mm [$^1/_4$ in] tall, at the top of the cut plane and/or moderate variance in size and percent area of coarse aggregate distribution from top to bottom
3	unstable	Clearly segregated as evidenced by a mortar layer greater than 25 mm [1 in] tall and/or considerable variance in size and percent area of coarse aggregate distribution from top to bottom

A.9 Sieve Segregation Test (EN 12350-11)

PRINCIPLE: The amount of material passed through a sieve with 5 mm [0.2 in] square openings in a container is a measure of segregation.

PROCEDURE: A sample of 10 litres [2.6 GAL] (± 0.5 l) of fresh concrete is stored for 15 minutes, in a bucket with a lid to avoid evaporation. Weigh an empty container, put the (dry) sieve on top and weigh again, or set the balance to zero. After 15 minutes resting time take off the lid from the bucket and check for bleed water (record observation).

Fill an amount of 4.8 kg [10.6 lbs] (± 0.2 kg) of the concrete sample (including any bleed water) from a falling height of 500 mm [20 in] (± 50 mm) continuously and carefully onto the sieve. After 120 s (± 5 s), remove the sieve vertically without vibration. The amount of material in the container is recorded as the segregated portion in % of the mass poured onto the sieve.

REMARKS: -

A.10 Manual Vane Shear Test

PRINCIPLE: The shear resistance of a fresh concrete is a measure of its yield stress. This test is intended to evaluate thixotropic properties of fresh concrete by evaluating the structuration rate (yield stress increase over time when concrete is left at rest).

PROCEDURE: Prepare a specimen of a fresh concrete sample in a bucket of sufficient volume and about 20 cm [8 in] in height. On the gauge of the torque meter, move the pointer counter-clockwise to zero.

Gently lower the shear vanes into the specimen without disturbing the concrete sample. The top of the vanes should be at least 50 mm [2 in] below the top of the concrete. Rotate the vane shear tester manually with a slow controlled movement and read the maximum torque.

REMARKS: A difference in torque measured in fresh concrete before and after resting is an indication of the concrete's thixotropy. Use up to 5 vane cells to test a series of concrete specimens at different resting times. Insert a cell in each specimen and test for its shear e.g. instantly and after 2, 4, 8 and 15 minutes. The increase of yield stress is a direct measure for the concrete's thixotropy and can be calculated as structuration rate A_{thix} (in Pa/min), see Roussel and Cussigh, 2008.

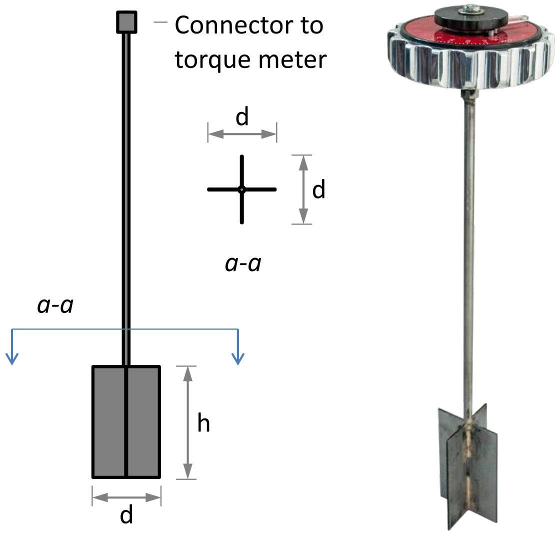
A 100% increase in 15 minutes might be assessed as excessive thixotropy. For absolute assessment of allowable thixotropy a correlation to slump-flow must be established.

In order to ensure sufficient selectivity the vanes shall be adapted, compared to typical vanes used for cohesive soils. The vane shear cell shall have a height of h = 100 mm [4 in] and a diameter of d = 60 mm [2 in] (4 blades at 90 degree angle each 30 mm [1 in] wide), see *Figure A.4*. The axle shall be of sufficient length (about 300 mm [12 in]) so that the vanes can be lowered well below the concrete surface.

Note 1: A diameter of 50 mm [2 in] for the vane shear cell is also considered acceptable.

Note 2: Concrete thixotropic tendency can be tested using the slump-flow equipment (see A.1): Fill two slump cones with fresh concrete and perform one slump-flow test immediately. After a resting period of 15 minutes, perform the second slump-flow test. If the difference in values is greater than 30 mm [2 in] the test should be repeated.
Preliminary findings from the Research and Development Project indicate that thixotropy is significant in cases where the slump-flow after 15 minutes of rest is 50 mm [2 in] (or more) below the initial value.

FIGURE A.7 AXIS AND VANE SHEAR CELL DIMENSIONS FOR THE MANUAL VANE SHEAR TEST (NEW ZEALAND GEOTECHNICAL SOCIETY, 2001)



Appendix B

Concepts for Use of Additions

Specified minimum cement contents for concrete in deep foundations are often not necessary to obtain the required strength class, but to obtain specific fresh properties. Additions like fly ash and GGBS are often used to replace part of the cement, which in turn affects the fresh concrete's workability, flow retention and stability, as well as strength, durability and overall sustainability.

Three concepts are available for the use and application of (reactive) Type II additions (EN 206):-

1. The k-value concept,
2. The Equivalent Concrete Performance Concept (ECPC) and
3. The Equivalent Performance of Combinations Concept (EPCC).

The rules for the application of the three concepts vary within the different CEN member states. For each project, the concept should be carefully considered, both from a technical and an economical point of view.

K-Value Concept

The k-value concept is a prescriptive concept. It is based on the comparison of the durability performance of a reference concrete with another one in which part of the cement is replaced by an addition as a function of the water/cement ratio and the addition content.

The k-value concept permits type II additions to be taken into account:-

- by replacing the term "water/cement ratio" with "water/(cement + k * addition) ratio" and;
- the amount of (cement + k * addition) shall not be less than the minimum cement content required for the relevant exposure class.

The rules of application of the k-value concept for fly ash conforming to European standard EN 450-1, silica fume conforming to EN 13263-1, and ground granulated blast furnace slag conforming to EN 15167-1 together with cements of type CEM I and CEM II/A conforming to EN 197-1 are given in corresponding clauses in EN 206.

Modifications to the rules of the k-value concept may be applied where their suitability has been established (e.g. higher k-values, increased proportions of additions, use of other additions, combinations of additions and other cements).

For a further description of the full procedure and application of the k-value concept, the reader is referred to CEN/TR 16639.

Equivalent Concrete Performance Concept (ECPC)

The principles of the Equivalent Concrete Performance Concept have been introduced in EN 206.

This concept permits amendments to the requirements for minimum cement content and maximum water/cement ratio when a combination of a specific addition and a specific cement source is used where the manufacturing source and characteristics of each are clearly defined. It shall be proven that the concrete has an equivalent performance especially with respect to its interaction with the environment and to its durability when compared with a reference concrete in accordance with the requirements for the relevant exposure class.

The reference cement shall fulfil the requirements of EN 197-1 and originates from a source that has been used in practice in the place of use within the last five years and used in the selected exposure class. The reference concrete shall conform to the provisions valid in the place of use for the selected exposure class.

The constituents for designed and prescribed concrete shall be chosen to satisfy the requirements specified for fresh and hardened concrete, including consistence, density, strength, durability, and protection of embedded steel against corrosion, taking into account the production process and the intended method of execution of concrete works.

Equivalent Performance of Combinations Concept (EPCC)

The principles of the "Equivalent Performance of Combinations Concept" permit a defined range of combinations of cement conforming to European standard EN 197-1 and addition (or additions) having established suitability that may count fully towards requirements for maximum water/cement ratio and minimum cement content which are specified for a concrete.

The elements of the methodology are:-

1. Identify a cement type that conforms to a European cement standard and that has the same or similar composition to the intended combination
2. Assess whether the concretes produced with the combination have similar strength and durability as concretes made with the identified cement type for the relevant exposure class
3. Apply production control that ensures these requirements for the concretes containing the combination are defined and implemented.

In Europe there are three methods applied to establish the equivalent performance of combinations - the UK method, the Irish method and the Portuguese method. These three methods have been developed separately and differ considerably in the requirements for the control of the combinations. The three methods are fully described in CEN/TR 16639.(2014).

Appendix C

Methods for Testing Completed Works

Testing of completed works may or may not be mandatory for geotechnical works but where specified, is done for post construction verification of completed works, in addition to production of construction inspection records. Generally, tests are used according to project specifications. Some tests need to be prepared before execution of the deep foundation, others can still be applied when there is reason to suspect an imperfection exists (see *Appendix D*).

Non-destructive testing can be effective in validating the integrity of a deep foundation without the need for intrusive investigation. It can also identify anomalies in the data, indicating possible imperfections, but testing cannot prevent imperfections. Effective means of avoiding imperfections are:

- Appropriate design, including proper detailing of reinforcement cages (refer *Appendix E*)
- Installation by a qualified and experienced deep foundation contractor
- Consistent supply of sufficiently workable and stable concrete at a batching plant with appropriate quality control measures
- Foundation construction testing (including fresh concrete testing) and inspection by knowledgeable and attentive personnel

Also common to all integrity test methods is the need for thorough, complete records of installation. Such records are essential to allow proper interpretation of test results and to distinguish between anomalies and imperfections.

Both destructive and non-destructive testing methods require expert knowledge for performance and interpretation. Technician-level expertise is required for conducting the tests while interpretation of results should be done by a qualified engineer, in consultation with the project's responsible engineer.

In addition to the list of destructive testing methods, low strain dynamic testing, crosshole sonic logging (CSL) and thermal integrity profiling (TIP) are described representing the common non-destructive testing methods which require detailed pre-planning in advance of construction. These methods are also described in Recommendations on Piling (2012), ICE SPERW (2017), FHWA GEC 10 (2018), and expert literature for non-destructive testing. The methodology specific limitations need to be understood prior to applying these methods.

If testing of completed works is required, non-destructive testing (NDT) should be the first choice, in preference to destructive testing. Destructive testing is often performed when NDT methods reveal potential imperfections that require further investigation.

Non-destructive Testing Methods

Low-Strain Dynamic Testing

Low-strain dynamic testing, also known as pile impact or pile integrity testing (PIT), sonic echo or transient dynamic response method, is a "Standard Test Method for Low Strain Impact Integrity Testing of Deep Foundations" (ASTM D5882). Pile head motion is measured during impact of a handheld hammer which transmits an acoustic wave down the pile and is reflected back to the pile head. Experienced interpretation is needed. The test can in some instances be effective for identifying major imperfections, that produce significant changes in foundation diameter or stiffness. The effective test depth is limited by pile length/diameter ratio and therefore not suitable to deep piles.

Crosshole Sonic Logging

Crosshole sonic logging (CSL) involves transmission of an acoustic wave from a transmitter embedded within a pre-installed duct within the foundation element to a receiver positioned in a separate duct. The test method is detailed in ASTM D6760-14, NF P94-160-1, ICE SPERW (2017) and CIRIA R144.

The time for the wave to reach the receiver and the energy transmitted is measured and used to interpret the result. Significant increases in travel time and/or decreased energy are interpreted as ultrasonic anomalies (i.e. potential imperfections). Interpretation criteria recommended by DFI's white paper *Terminology and Evaluation Criteria of Crosshole Sonic Logging (CSL) as applied to Deep Foundations* (2019) consider both the delay in arrival time and reduction in energy. The paper recommends holistic evaluation of the foundation.

CSL ducts are typically located in an array within the reinforcing cage of the foundation. The ability to obtain sonic profiles between multiple pairs of tubes may provide an indication of the nature, position and dimension of a possible imperfection within the centre of the reinforcing cage and around the duct. It cannot provide any indication of possible imperfections in the cover zone, i.e. between the reinforcing cage and the face of the excavation. It is important that the space between tubes is not obstructed as this will cause anomalous readings. Close tube spacings can also give rise to anomalous readings that do not reflect integrity.

The test is sensitive to variations in both the actual velocity within the concrete and the accuracy of tube positioning, and interpretation as well as assessment needs expert knowledge and should include all available information related to execution (Beckhaus and Heinzelmann, 2015). The location of tube connections, for example, can affect results locally.

It has been shown that, in principle, the integrity between diaphragm panels or two secondary secant piles (including the primary pile between) can be investigated if tubes are installed either side of the joint(s) (Niederleithinger et al, 2010). The results from such measurements may, however, be difficult to assess due to the presence of 'cold' joints between the elements. This test is not applicable where preformed stop ends are used, such as precast concrete or steel elements.

Thermal Integrity Testing

Thermal integrity testing involves measuring the temperature of the concrete during hydration. Temperature is measured with sacrificial cables installed along the full length of a foundation element at multiple points around the circumference of the reinforcing cage. The differences in thermal conductivity and heat generation of any inclusions produce a variation in temperature that can be identified from the temperature records. The test method is detailed in US standard ASTM D7949 and in the UK in ICE SPERW (2017).

The concrete temperature is monitored by looped strings of thermistors, distributed fibre optic sensing methods or, occasionally, thermal probes are used, guided in tubes within the foundation element. The thermal probe method is not recommended, as it fails to capture a complete time record of temperatures, and the time record is typically critical for identifying imperfections (e.g., Boeckmann, et al., 2022). These systems are generally attached to the reinforcement cage and so measure the temperature in the cover zone of the foundation element, in addition to sensing some distance into the pile core. Intellectual Property rights may apply to different proprietary systems.

In most applications, lack of increase in temperature could indicate a local thermal anomaly (i.e. a reduction or absence of hydrating cement). The thermal data can be acquired throughout the shaft, allowing for a full 360° assessment to be undertaken. Temperatures are affected by concrete within the core of the shaft as well as the cover zone, ground conditions, and alignment of the reinforcement, among other factors. Any changes in temperature within a foundation can therefore explained by several potential factors, with an element-specific evaluation that considers installation records required for interpretation of thermal results. Piles extending through water are particularly susceptible to thermal effects that can be misinterpreted as imperfections.

Synthesizing the results of two full-scale field investigations of bored piles with known imperfections and thermal testing, Boeckmann, et al. (2022) made the following recommendations for interpretation of thermal testing results:

- Construction records, including drilling records, bottom-of-shaft inspection forms, and accurate concrete volume logs should be reviewed to identify any potential imperfections.
- Temperature versus depth plots should be reviewed to identify any potential zones with unusual temperatures that may indicate imperfections. The temperature-depth plots should be prepared for the time of peak temperature, half the time of peak temperature, and potentially earlier times (especially for concrete mixes with significant amounts of SCMs or retarder).
- Any potential imperfections should be considered in the context of construction records.
- For any depths with potential imperfections, temperature versus time plots should be evaluated. The temperature-time plots should include records from each thermal cable for the depth of the suspected imperfection as well as from a nearby depth that appears to be uninfluenced by the imperfection.

In addition to these recommendations, review of a time lapse video of the concrete curing from thermal testing results is recommended for all evaluations of thermal data. Such time lapse videos are a common feature in thermal testing software.

Thermal testing technology can also be used to track concrete flow within the pile or panel during the tremie concrete process by monitoring the difference in temperature between the support fluid and concrete in real time.

Destructive Testing Methods

Destructive testing of foundations should be carefully planned and executed. They are often time consuming and expensive and usually undertaken in a limited targeted approach, when NDT is not possible, or when NDT requires further investigation. Some examples are:

- Coring within the foundation to investigate features within the element, or to inspect the condition at the base. For the latter case, ducts may be installed attached to the reinforcing cage and extended to near the base to facilitate coring if planned in advance.
- Closed circuit television (CCTV) inspection of the foundation and its base, inside a drilled core hole.
- Excavation to inspect the surface of the foundation.
- Extraction of a pile.

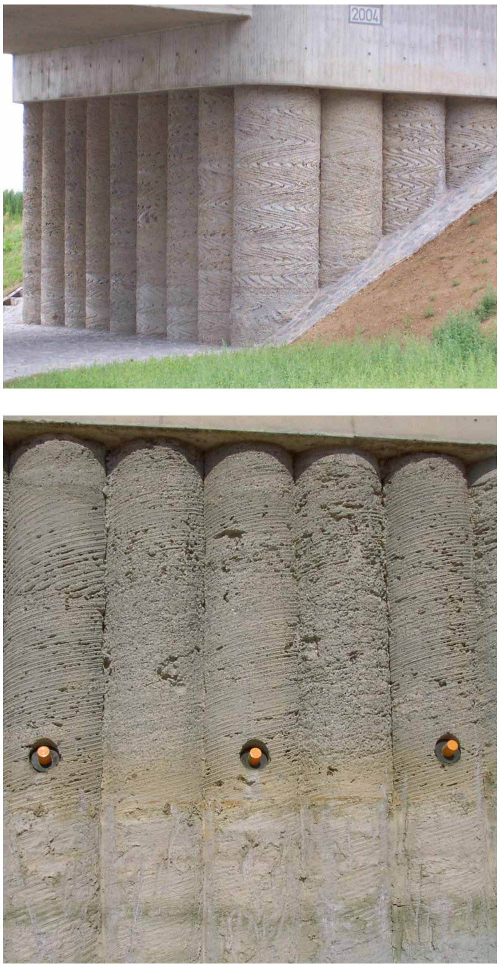
Appendix D

Types of Imperfections

Imperfections within a deep foundation element, by definition, deviate from the planned shape, material and/or regular continuity of the cast in-situ concrete element. Imperfections may or may not affect foundation performance and are usually subject to further inspection. Any imperfection that, because of size, location and/or concrete properties, has a significant adverse effect on the performance of the foundation is then considered a defect.

For example, imperfections that are not defects are marks in the concrete surface of piles from withdrawn excavation tools which are often inevitable (see *Figure D.1*). Such grooves should not be considered as defects, as long as they do not compromise the structurally required minimum concrete cover after execution. More significant imperfections may also not qualify as defects. For example, an inclusion that occurs in a zone of low bending and shear demand may not be a defect, whereas an otherwise similar inclusion that occurs at the depth of maximum bending moment may well render the foundation defective.

FIGURE D.1 EXAMPLES FOR PILES WITH GROOVES, NOT AFFECTING THE MINIMUM COVER FOR DURABILITY



Most imperfections related to the concrete tremie process will fall into one of the following three categories: inclusions, bleed channels or mattressing. Examples and details are given below.

Inclusions

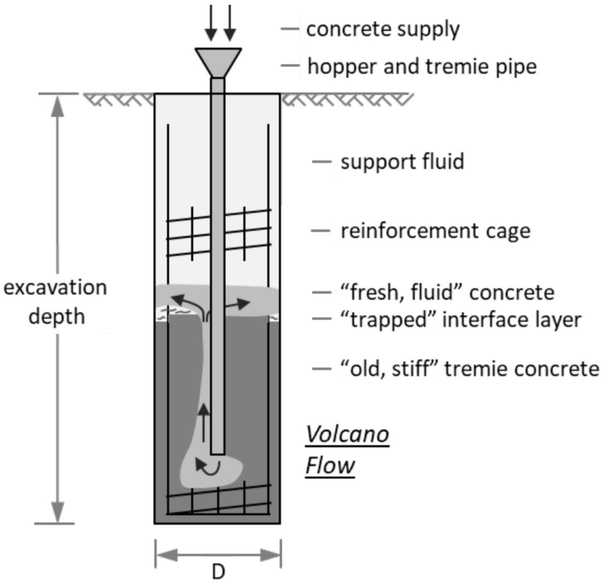
Inclusions consist of entrapped material within the foundation, including at the pile base, that does not conform to the reference concrete. It can be material originating the surrounding ground (e.g. soil, rock or groundwater) or poorly cemented material originated from segregated concrete. Entrapped material can also be a mixture of the support fluid, concrete and/or excavated ground, such as from the interface layer. Two examples are shown in *Figure D.2*.

FIGURE D.2 EXAMPLES OF INCLUSIONS OF A DIAPHRAGM WALL PANEL AND PILES

Inclusions are usually considered acceptable if limited in their extent and frequency. Only if these are of such dimensions that they reduce the bearing capacity to a value less than required by design, or occupy wide parts in the cover zone and can therefore reduce durability, should inclusions be classified as defects. Contrary to a regular flow pattern (as shown in *Figure 16* and *Figure 17*), the "volcano flow" in *Figure D.3* illustrates an irregular flow pattern where the "fresh, fluid concrete" is not able to displace the "old, stiff concrete" (over a large area of the cross-section). This may lead to inclusions. Inclusions may be associated with a single source within the field of detailing, concrete or execution. The cause of inclusions typically includes one or more of the following;

- Congested and/or poorly detailed reinforcement cages inhibiting concrete flow and support fluid displacement.
- Incorrect selection and management of support fluid, encouraging shaft/panel wall instability before and during the concreting process.
- Incorrect tremie concrete operation with insufficient or too much tremie pipe embedment. In the extreme, removal and reinsertion of the tremie pipe from the concrete part way through the pour.
- Unplanned delays in between concrete pours allowing poured concrete to lose in-situ workability.
- Insufficient cleaning of the excavation base and support fluid prior to concreting, or excessive built-up of an interface layer during the pour.
- Unsuitable concrete design and verification process, producing concrete with poor workability and stability properties.

FIGURE **D.3** **SCHEMATIC OF A VOLCANO FLOW DUE TO LOSS IN CONCRETE MIX WORKABILITY DURING TREMIE PLACEMENT (ACCORDING TO FIGURE 9.13, FHWA GEC10), WHERE AN INTERFACE LAYER CAN PARTLY BE ENTRAPPED BY CONCRETE AND FORM AN INCLUSION.**



Non-destructive testing can assist in identifying inclusions (see *Appendix C*). These tests need special knowledge and experience with which the imperfection's extent might be assessed by further evaluations.

Bleed Channels

Bleed channels is also referred to as channelling. These are vertical narrow zones with lightly cemented aggregate with a lack of fines and cement matrix, usually near the surface of the panel or pile or next to reinforcing bars or crosshole sonic logging access ducts. This phenomenon is due to an insufficient stability of the concrete (poor segregation or bleeding resistance) for the actual ground and placement conditions.

Bleed channels are usually not considered defects if they are isolated and of limited thickness, thus not reducing the durability significantly (see *Figure D.4*). In addition, bleed water can pass up around vertical installations within the cross-sections e.g. vertical reinforcement bars, or within the core of wide elements. Bleeding along crosshole sonic logging access ducts is a cause of anomalous test results. Bleed water is attracted to the smooth ducts and can produce debonding of the ducts from the concrete and therefore anomalous results.

FIGURE **D.4** **EXAMPLES OF CHANNELS RUNNING UP THE SURFACE OF A PILE AND A DIAPHRAGM WALL**

Mattressing

Mattressing refers to the situation wherein tremie concrete does not completely fill the cover zone, instead leaving "shadows" or creases with trapped laitance behind the reinforcing bars. For extreme cases, the resulting surface pattern resembles a mattress top, as shown in the photographs of *Figure D.5*, which show excavation support elements revealed to have mattressing after excavation. Mattressing leads to concerns about concrete-reinforcement bond strength and potential corrosion of the reinforcing cage. Mattressing is a potential result of reinforcing cages with insufficient clear spacing or insufficiently workable concrete. The use of box-outs will also encourage this as they interrupt vertical flow of concrete within the cover zone.

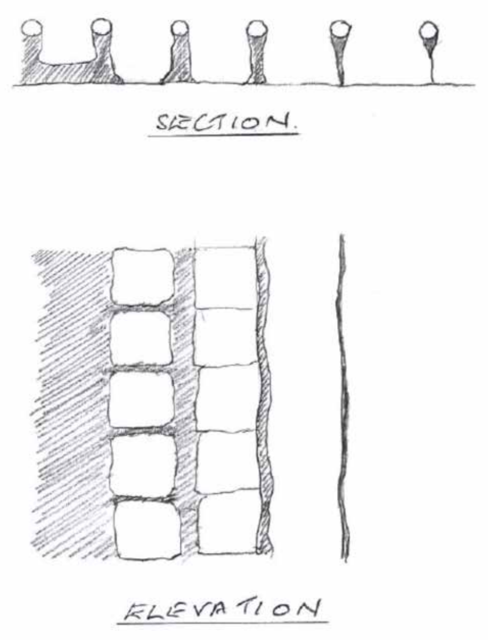
Whereas light mattressing describes vertical linear features emanating primarily from vertical reinforcing bars (right side of *Figure D.6*), heavier more pronounced mattressing reflects intersecting vertical and horizontal linear features (left side of *Figure D.6*). Both features emanate at the reinforcement with material trapped in the shadow of the reinforcing bars. Vertical mattressing features may provide a pre-defined route for bleed water leading to a combination of imperfections.

Mattressing can interrupt the entire depth of concrete cover to the reinforcement. It can have a detrimental effect on durability, structural or bearing capacity (depending on the extent and frequency) and can be significant. Significant mattressing should be interpreted as a possible defect, and investigated further (see *Figures D.5 and D.6*).

The formation of mattressing is associated with restricted horizontal flow of concrete through reinforcement into the cover zone combined with insufficient vertical flow and therefore with a lack of free flow around reinforcement bars. The energy applied to the fresh concrete, its flowability, stability and passing ability, in combination with the cage congestion and concrete cover dimension can all contribute to the extent of this imperfection. Mattressing is likely to be more prevalent at higher elevations where hydrostatic pressure is reduced.

FIGURE D.5 SHADOWING IN A PILE (LEFT); MATTRESSING IN A PANEL (RIGHT)

FIGURE D.6 SCHEMATIC SHOWING VARYING DEGREES OF MATTRESSING



As for other types of imperfections, the particular features of the mattressing can reveal its formation mechanism. But as for the other types, it is also for mattressing often the case that it can have multiple causes and that is why specialist knowledge and experience, and construction documentation are required. Some of the following features and associated questions may assist to find relevant causes:

- Cover zone location – can the imperfection be related to dense reinforcement or obstructions in the cover zone?
- Extent of imperfections – is a variation of cover thickness related to the occurrence?
- Type of material entrapped – is the material excavated ground or solely comprised of concrete materials?
- Construction irregularities – do the concrete placement and tremie pipe embedment records reveal issues during construction?
- Concrete workability retention – is the admixture system or dosage according to the workability retention specified, was placement delayed excessively after truck arrival, was the ambient temperature during production excessive, or was any irregularity in batching observed?
- Instability of concrete – is there a presence of a thick interface layer of material rising on top of the concrete, channel features on the exposed face, or a lack of aggregate in concrete pointing to excessive segregation?

If imperfections are assessed to be defects and if these are frequent, it can be possible to postulate an imperfection formation mechanism, which if detected early enough will enable changes to detailing, materials or construction processes to avoid further occurrences.

Appendix E

Detailed Information on Design Considerations

This Appendix should be read in conjunction with *Section 2* and includes supplementary information on detailing, concrete cover, single columns on single piles, all related to the impact on concrete flow.

Detailing

The detailing of deep foundation structures should only be carried out by experienced personnel.

Every effort must be made to ensure that reinforcement is not congested and satisfies the minimum clear spacing rules as given in relevant standards. Where a high density of reinforcement is required the maximum available bar diameter and maximum bar spacing should be used. Where multiple layers are needed special focus must be given to the maintenance of sufficient concrete flow (see *Sections 3* and *6*). It is often the case that very dense reinforcement indicates that the dimensions of the deep foundation element need to be increased.

Additional constraints on reinforcing cage layout also include:-

- Additional reinforcement to allow lifting and placing (e.g. stirrups and cross-bracings)
- Space for the stop end (where used)
- Space for the tremie pipe
- Instrumentation
- Width and length constraints due to transportation restrictions
- The weight of the reinforcement cage
- Items in the cover zone such as spacers, box outs or couplers
- Tie-back sleeves and other embedded items such as utility blockouts, etc.

Detailing requirements for cages are summarized in *Tables E.1, E.2* and *E.3*.

Note: The tables refer to the relevant version of the codes or norms at the time of producing this Guide. A check must be made to ensure that the code or norm has not been updated after the publication of this Guide.

Structural codes like EN 1992 or ACI 318 set general normative regulations for the detailing, in particular for the spacing and the concrete cover of structural elements. These are also valid for deep foundations i.e. for their structural design. Execution tolerances, such as the dimensions of the reinforcement cage, are considered, but these cannot cover all the specific tolerances for deep foundations. Subsequently, execution standards like EN 1536 and EN 1538 set additional regulations, leading sometimes to conflicting interpretations.

Reinforcement Clear Spacing

The clear spacing between reinforcement bars affects the ability of concrete to flow into the cover zone, and must be appropriate for the actual conditions. This is difficult to quantify as it requires consideration of the spacing between horizontal and vertical bars, clear window size, the layout of multiple rows of reinforcement, the concrete aggregate size, and the rheology in connection with flow distances and hydrostatic pressures. Transverse reinforcement which runs through the centre of the reinforcing cage, (couplers, links, tie rods etc.) affects the vertical upward flow of the concrete.

There is consensus that spacing of reinforcement bars for deep foundations shall be much higher than required by the structural codes, due to the onerous execution requirements.

As set out in *Section 2.2*, a minimum clear spacing on vertical of 100 mm [4 in] should be mandatory. FHWA GEC10 recommends values from 5 to 10 times the maximum aggregate size for difficult installation conditions i.e. very large or very deep elements, multiple bar layers and intricate cage geometry. This also includes splice zones or where bars are connected with couplers.

It is hoped that future research by computational simulations, validated by field trials, may assist in establishing better rules for the appropriate clear spacing.

TABLE E.1 COMMONLY USED REINFORCEMENT REQUIREMENTS FOR BORED PILES AND BARRETTES

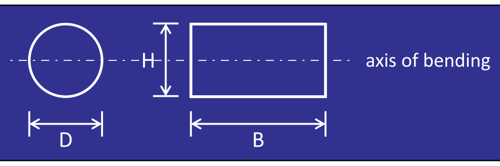
MINIMUM REINFORCEMENT FOR BORED PILES AND BARRETTES				
LOCATION	**CLAUSE**	**VALUE**	**COMMENTS**	
For elements where the load eccentricity does not exceed D/8 for piles, or H/6 for barrettes				
Vertical	AASHTO LRFD 5.12.9 (2020)	$\geq 0.8\%\ A_c$	where A_c is nominal cross-sectional area	
	ACI336.3R-14, 4.6, referring to ACI318 (see ACI318-19, 10.6.1)	$\geq 1\%\ A_c$	for elements that cannot be designed as plain concrete, where A_c is nominal cross-sectional area.	
	EN1992-1-1:2023, Table 12.3 (NDP)	max $\{10\%\ N_{Ed} / f_{yd};\ 0.2\%\ A_c\}$	where N_{Ed} is the applied design load, f_{yd} is the design strength of the reinforcement and A_c is nominal cross-sectional area	
	EN1536:2010+A1, Table 3	$\geq 0.5\%\ A_C$	$A_C \leq 0.5m^2$	where A_C is nominal bored pile cross section.
		$\geq 0.0025m^2$	$0.5m^2 < A_C \leq 1.0m^2$	
		$\geq 0.25\%\ A_C$	$A_C > 1.0m^2$	
Links, hoops or spiral reinforcement	AASHTO LRFD 5.12.9 (2020)	≥ 5.7 mm	at a pitch of 150 mm	
	ACI336.3R-14, 4.6 referring to ACI318 (see ACI318-19, 10.6.2)		ACI318-14, 10.6.2.2 gives minimum area of spiral reinforcement	
	EN1536:2010+A1, Table 4	$\geq$ 6mm $\geq$ one quarter of the maximum diameter of the longitudinal bars	Links, hoops or spiral reinforcement.	
		$\geq$ 5mm	wires of welded mesh transverse reinforcement.	
For elements where the load eccentricity exceeds D/8 for piles, or H/6 for barrettes				
Vertical	EN1992-1-1:2023, 12.2(2) and Table 12.3 (NDP)	$(f_{cm}/f_{yk})\ A_c / [1+N_{Ed}/(f_{ctm}.A_c)]$, but not less than max $\{10\%\ N_{Ed} / f_{yd};\ 0.2\%\ A_c\}$	where where A_c is the nominal cross-sectional area, f_{cm} is the mean tensile strength of the concrete, which can be taken as $0.3f_{ck}2/3$ for $f_{ck} \leq 50N/mm^2$ and $1.1f_{ck}1/3$ for $f_{ck} > 50N/mm^2$, f_{yk} is the yield strength of the reinforcement and f_{yd} is the design strength of the reinforcement (this expression assumes one quarter of the total reinforcement controls the cracking on the tensile face, resisting the tensile force taken by the concrete prior to cracking)	
Links, hoops or spiral reinforcement (where required for shear strength)	EN1992-1-1:2023, 12.2(4)	area of link or spiral reinforcement for pile $\geq 0.08\ [f_{ck}]^{1/2}/f_{yk}$ area of link for barrette $\geq 0.08\ [f_{ck}]^{1/2}/f_{yk}$	where s is the spacing of the links or pitch of the spiral reinforcement, fck is the characteristic strength of the concrete (N/mm^2) and fyk is the yield strength of the reinforcement	
	EN1992-1-1:2023, Table 12.1 (NDP)	vertical spacing of links for piles ≤ 0.6 D vertical spacing of links for barrettes ≤ 0.6 H pitch of spiral reinforcement ≤ 0.3 D	(this assumes that the effective depth is around 0.8 D for piles or 0.8 H for barrettes and that the potential failure plane intersects spiral reinforcement at least three times)	

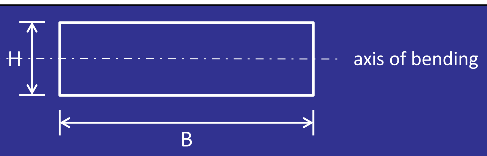
TABLE E.1 COMMONLY USED REINFORCEMENT REQUIREMENTS FOR BORED PILES AND BARRETTES cont.

CLEAR SPACING FOR BORED PILES AND BARRETTES

LOCATION	CLAUSE	VALUE	COMMENT
Horizontal and vertical spacing of bars	AASHTO LRFD 5.12.9 (2020)	$\geq 5\ D_{max}$ and ≥ 125 mm	where D_{max} = maximum aggregate size
Horizontal and vertical clear spacing of bars	ACI336.1-01, 3.4.9	≥ 100 mm	including at laps.
	ACI336.1-01, 3.4.9	$\geq 4\ D_{max}$	where D_{max} = maximum aggregate size, including at laps.
	EN1536:2010+A1, 7.5.2.5	≤ 400 mm	as wide as possible, but less than 400 mm.
	EN206:2013+A2:2021, Annex D.2.2 (see also BS8500-1:2023 and BS8500-2:2023)	$c_s \geq 4\ D_{upper}$	where c_s is the clear spacing between bars and D_{upper} is the largest value of the upper sieve size for the coarsest fraction of aggregates in the concrete permitted by its specification
	EN1536:2010+A1, 7.5.2.6 and 7.6.3.3	≥ 100 mm	for single or bundles of longitudinal bars. The same value applies to horizontal (transverse) bars
	EN1536:2010+A1, 7.5.2.7	≥ 80 mm	for lap length, provided that the maximum size of the aggregate $\leq$ 20mm (special consideration must be given to the maintenance of sufficient concrete flow, see *Sections 3 and 6*).
	EN1536:2010+A1, 7.5.2.9	$\geq 1.5\ D_{max}$ and $\geq 2.0\ D_S$	for layers of bars, placed radially, where D_{max} is the maximum size of the aggregate and D_S is the (steel) bar diameter.

TABLE E.2 COMMONLY USED REINFORCEMENT REQUIREMENTS FOR DIAPHRAGM WALLS

MINIMUM REINFORCEMENT FOR DIAPHRAGM WALLS



LOCATION	CLAUSE	VALUE	COMMENT
Vertical - for walls where the load eccentricity does not exceed H/6	EN1992-1-1:2023, Table 12.4 (NDP)	where wall carries vertical in-plane compression and in-plane shear: minimum area in each face / unit length $\geq$ 25% H (f_{ctm}/f_{yk}) where wall is only loaded by vertical in-plane compression: minimum area in each face / unit length: > 0.1% H	where f_{ctm} is the mean tensile strength of the concrete, which can be taken as $0.3f_{ck}^{2/3}$ for $f_{ck} \leq 50N/mm^2$ and $1.1f_{ck}^{1/3}$ for $f_{ck} > 50N/mm^2$, and f_{yk} is the yield strength of the reinforcement
	EN1538:2010+A1, 7.5.3.1	$D_S \geq 12$ mm	where D_S is the (steel) bar diameter
	EN1538:2010+A1, 7.5.3.1	> 3 bars / m	on each side of the reinforcement cage
Vertical - for walls where the load eccentricity exceeds H/6	EN1992-1-1:2023, 12.2(2) and Table 12.4 (NDP)	where wall carries vertical in-plane compression and in-plane shear: minimum area in each face / unit length $\geq$ 25% H (f_{ctm}/f_{yk}) where wall is only loaded by vertical in-plane compression: minimum area in each face / unit length: minimum area in each face / unit length $\geq$ 25% H (f_{ctm}/f_{yk})/ (1+N_{Ed}/(f_{ctm}.H)), but > 0.1%H	where f_{ctm} is the mean tensile strength of the concrete, which can be taken as $0.3f_{ck}^{2/3}$ for $f_{ck} \leq 50N/mm^2$ and $1.1f_{ck}^{1/3}$ for $f_{ck} > 50N/mm^2$, f_{yk} is the yield strength of the reinforcement and N_{Ed} is the compression in the wall / unit length (this expression assumes that the reinforcement resists the tensile force taken by the concrete prior to cracking)
	EN1538:2010+A1, 7.5.3.1	$D_S \geq 12$ mm	where D_S = (steel) bar diameter
	EN1538:2010+A1, 7.5.3.1	> 3 bars / m	on each side of the reinforcement cage
Horizontal	EN1992-1-1:2023, Table 12.4 (NDP)	where wall carries vertical in-plane compression and in-plane shear: minimum area in each face / unit height $\geq$ 25% H (f_{ctm}/f_{yk}) where wall is only loaded by vertical in-plane compression: minimum area in each face / unit height: > 0. 25 $A_{s,v}$	where f_{ctm} is the mean tensile strength of the concrete, which can be taken as $0.3f_{ck}^{2/3}$ for $f_{ck} \leq 50N/mm^2$ and $1.1f_{ck}^{1/3}$ for $f_{ck} > 50N/mm^2$, and f_{yk} is the yield strength of the reinforcement $A_{s,v}$ is the vertical reinforcement / face / unit length
	EN1992-1-1:2004+A1, 9.6.3	minimum area in each face / unit height $\geq$ 25% A_{sv}	where A_{sv} is the area of vertical reinforcement in face / unit length
	EN1538:2010+A1		no specific requirements
Through-thickness links (where required for shear strength)	EN1992-1-1:2023, 12.2(4)	minimum area / unit area of wall (in elevation) $(0.08\,[f_{ck}]^{1/2)})/f_{yk}$	where f_{ck} is the characteristic strength of the concrete and f_{yk} is the yield strength of the reinforcement
	EN1992-1-1:2023, Table 12.1 (NDP)	horizontal spacing $\leq$ 0.75 d, but not more than 600 mm	where d is the effective depth to the centroid of the tension reinforcement from the compression face
	EN1992-1-1:2023, Table 12.1 (NDP)	vertical spacing $\leq$ 0.75 d	

TABLE E.2 COMMONLY USED REINFORCEMENT REQUIREMENTS FOR DIAPHRAGM WALLS cont.

CLEAR SPACING FOR DIAPHRAGM WALLS			
LOCATION	**CLAUSE**	**VALUE**	**COMMENT**
spacing of vertical bars	EN206:2013+A2, Annex D.2.2 (see also BS8500-1:2023 and BS8500-2:2023)	$\geq 4\ D_{upper}$	D_{upper} is the largest value of the upper sieve size for the coarsest fraction of aggregates in the concrete permitted by its specification.
	EN1538:2010+A1, 7.5.3.2	≥ 100 mm	of single bars or groups, parallel to the wall face.
	EN1538:2010+A1, 7.5.3.3	≥ 80 mm	for the lap length, provided that $D_{max} \leq 20$mm (special consideration must be given to the maintenance of sufficient concrete flow, see *Sections 3 and 6*).
vertical spacing of horizontal bars	EN1538:2010+A1, 7.5.4.2	≥ 200 mm	
	EN1538:2010+A1, 7.5.4.3	≥ 150 mm	where required, provided that $D_{max} \leq 20$mm, where D_{max} is the maximum aggregate size.
horizontal spacing of transverse bars	EN1538:2010+A1, 7.5.4.4	≥ 150 mm	
	EN1538:2010+A1, 7.5.4.5	≥ 200 mm	recommended
horizontal spacing of adjacent cages	EN1538:2010+A1, 7.5.5.1	≥ 200 mm	
	EN1538:2010+A1, 7.5.5.2	≥ 400 mm	recommended
horizontal spacing of cages and joints incl. water-ends	EN1538:2010+A1, 7.5.5.3	≥ 100 mm	
	EN1538:2010+A1, 7.5.5.4	≥ 200 mm	recommended

TABLE E.3 **COMMON REQUIREMENTS FOR BOND, ANCHORAGE, LAPS AND CRACK WIDTH**

BOND, ANCHORAGE (DEVELOPMENT LENGTHS) AND LAPS (SPLICE LENGTHS) FOR BORED PILES AND DIAPHRAGM WALLS		
LOCATION	**CLAUSE**	**COMMENT**
Anchorage length („development length“)	AASHTO LRFD 5.10.8.2 (2020)	5.10.8.2.3 addresses bundled bars
Lap length	AASHTO LRFD 5.10.8.4 (2020)	
Anchorage length („development length“)	ACI318-19, 25.4.2	barsBars in tension.
	ACI318-19, 25.4.9	barsBars in compression.
Lap length	ACI318-1914, 25.5.2	bars in tension.
	ACI318-1914, 25.5.5	bars in compression.
	ACI318-1914, 25.6	additional rules for bundled bars.
	ACI318-1914, 10.7.5.2	additional rules for columns, which are assumed to apply also to piles.
Bond strength	EN1992-1-1:2023, 11.4.2(3)	if support fluid has not been used, bond conditions would normally be classified as ‘good’ with k_{cp} = 1.0 for both vertical and horizontal bars; and conditions are worse for bars executed under bentonite or similar slurries: in these circumstances k_{cp} should be taken as 1.4 unless data is available for the specific slurry to be used
Anchorage length	EN1992-1-1:2023, 11.4.2(3)	anchorage length can be calculated using Formula (11.3)
Lap length	EN1992-1-1:2023, Table 11.3	note that the lap length is a factored anchorage length; the definition of the clear distance cs for laps, used to determine the nominal cover, should be based on Figure 11.10 rather than Figure 11.3; the use of couplers should be considered, particularly for large bars.
CRACK WIDTHS		
LOCATION	**CLAUSE**	**COMMENT**
Calculation of crack widths	AASHTO LRFD 5.6.7 (2020)	Crack width is controlled by satisfying spacing requirements.
	ACI336.3R-14	no discussion of cracking
	ACI 318-19	The 2019 version does not present equations for predicting crack width. Rather, crack width is assumed to be controlled to generally acceptable levels if the reinforcement spacing methods are followed.
	ACI 224-01	Presents crack width equations from 1999 version of ACI 318. Table 4.1 presents „reasonable „ crack widths for concrete in different exposure conditions, iincluding soil (0.3 mm), seawater and wetting and drying (0.15 mm), and water retaining structures (0.1 mm).
	EN1992-1-1:2023, 9.2.3	

Concrete Cover

In terms of structural requirements, cover is required both for durability and to provide resistance to the splitting forces generated by the reinforcement bond.

For execution of deep foundations using concrete poured by tremie, provision of a suitable amount of cover, as stated in execution standards (EN 1536 and EN 1538, ACI 301), is critical to allow the concrete to flow around and completely embed the reinforcement bars to obtain dense durable concrete in this cover zone.

The greater of the individual minimum values for cover required from considerations of bond, durability and execution should be increased by an allowance for construction tolerance as shown in *Section 2.3*, and below.

Nominal cover = greater of minimum required for cover for durability, bond, execution + allowance for construction tolerance:-

$$c_{nom} = c_{min} + \Delta c_{dev} \text{ with } c_{min} \geq \max \begin{bmatrix} c_{min,\ structural} \\ c_{min,\ execution} \end{bmatrix}$$

The general recommendation of this Guide is that the minimum nominal cover for execution should be 75 mm [3in] i.e. a minimum cover of 50 mm [2 in] plus a tolerance of 25 mm [1 in].

The nominal cover should be increased in cases where the structural minimum cover e.g. as given in EN 1992, is greater than 50 mm [2 in] (as given above) by the corresponding amount.

Note 1: The minimum cover for execution should be increased if the conditions for concrete flow are considered critical. Some examples are given in EN 1536 such as where a large maximum grain size of 32 mm [1 1⁄4 in] is used or if the concrete viscosity is increased (e.g. where silica fume replaces cement by a considerable fraction of 5% or greater), or in soft soil without the use of a casing.

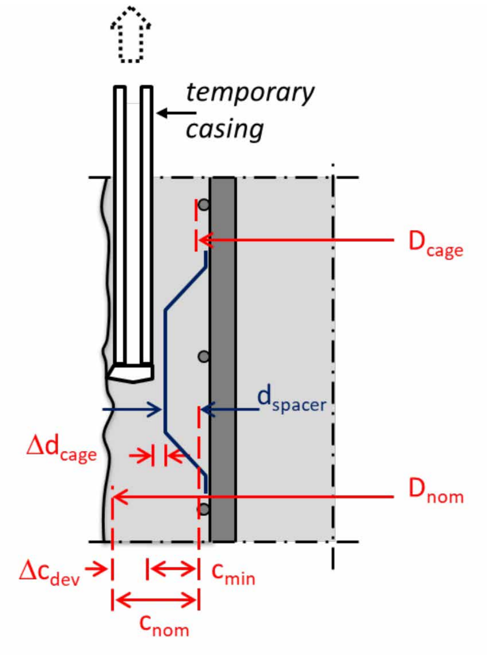
Note 2: FHWA GEC 10 (2018) suggests higher cover for larger diameter shafts i.e. 75 mm [3 in] cover for shafts of diameter not greater than 1 m [3 ft], 100 mm [4 in] cover for diameter greater than 1 m [3 ft] but not greater than 1.5 m [5 ft], and 150 mm [6 in] cover for diameter above 1.5 m [5 ft].

Note 3: EN 1536 permits the minimum concrete cover for execution to be reduced to 40 mm [1.5 in] to the external face of a permanent casing or lining, where used. It is recommended that the minimum cover of the reinforcement cage to the inner face of a casing, both temporary and permanent, should not be less than 50 mm [2 in]. An allowance for construction tolerances is not required in this case, but an additional tolerance for cage installation is still compulsory, see Figure E.1.

Note 4: The required distance between cages and joints or formwork ends are independent of the concrete cover. In accordance with EN 1538 +A1, 7.5.5.3 and 7.5.5.4 these distances should be ≥ 100 mm [4 in] and ≤ 200 mm [8 in] respectively.

Note 5: Many designers are reluctant to apply a large concrete cover on the basis that the crack width at the face may become excessive. This should not be a concern as crack width should only be calculated at the minimum cover position, with concrete outside that value being considered as surplus (see CIRIA Guide C760 (2017) and ACI 350).

FIGURE E.1 CONCRETE COVER IN BORED PILES SUPPORTED BY A TEMPORARY CASING (SUPPLEMENTING *FIGURE 3*)



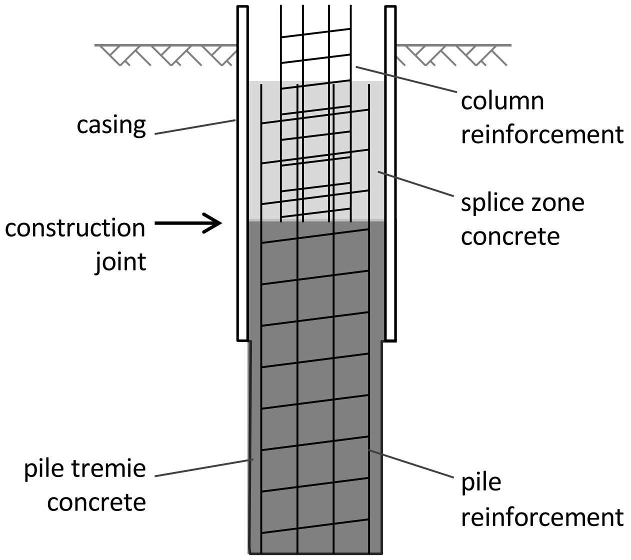
Single Columns on Single Piles

Cage connection details can present a challenge for constructability for bored piles where a single bored pile is used to support a single column and the splice between the column and pile reinforcement occurs near the top of the pile. This detail can be particularly congested where a non-contact lap splice is used and the column reinforcement comprises a separate cage within the pile reinforcement as shown on *Figure E.2*. Anchor bolt connections to transmission towers, sign poles, or similar structures also can result in congestion of this type. It is especially difficult for tremie concrete to make its way through two reinforcing cages without trapping fluid contaminants at the very top of the pile.

The most effective solution for this situation is to provide for a construction joint at a location below the splice, so that the pile head can be trimmed and the concrete at the splice connection can be cast in the dry as conventional structural concrete. This approach typically requires that a surface casing be used to provide a stable pile excavation above the construction joint. The surface of the construction joint would typically require preparation by removing any interface layer, bleed water, or contaminated concrete prior to concrete placement at the splice. In some cases it may be possible to remove fluids and contaminated concrete within the splice zone and complete the splice while the concrete remains workable.

In some cases where the overlap into the pile is relatively short (e.g. up to 2 m [7 ft]), it may be possible to insert the inner cage into the fresh concrete after the concrete placement has been completed. Although this approach would be unwieldy with a tall column cage, it may be manageable with a short section of reinforcement used to extend above grade as a splice cage or for an anchor bolt assembly. This process (commonly referred to as "wet-sticking") can have limitations if alignment tolerances are tight because of difficulties in precise placement and the short time window in which the concrete remains sufficiently flowable for the work to be completed.

FIGURE E.2 CONNECTION DETAILS FOR A BORED PILE USED TO SUPPORT A SUPERSTRUCTURE COLUMN



Appendix F

Selection of Factors and Effects on Concrete Flow

Appendix F / Selection of Factors and Effects on Concrete Flow

A selection of important factors and their possible effects on concrete flow within a deep foundation, and on the associated quality, is shown in *Table F.1*. This table reflects the common understanding of the Concrete Task Group. The list is not exhaustive, but allows a broad overview of the contents of this Guide.

TABLE F.1 **VARIOUS FACTORS AND THEIR POSSIBLE EFFECTS ON CONCRETE FLOW AND QUALITY OF DEEP FOUNDATIONS**

PARAMETER	RECOMMENDATION	EFFECT(S)	SEE
Clear reinforcement spacing	Maximise	Less blocking resistance and less resistance to concrete passing through. Minimises the risk of inclusions and insufficient embedment of the reinforcement bars by concrete.	2.2, App. E 6.8
Multiple layer reinforcement	Avoid	Less resistance to concrete passing through.	2.2
Concrete cover	Increase	Reduces risk for mattressing and may act as a safety margin for an unavoidable filter cake thickness.	2.2
Concrete rheology and workability	Medium/low yield stress Medium viscosity	High yield and high viscosity lead to poor flowability. Too low yield stress can cause instability. High variations in properties may contribute to irregular flow patterns.	3.2 4.3 6.7
Thixotropy	Control	Excessive increase in yield stress of concrete during unavoidable resting times may contribute to irregular flow patterns. In concrete finally placed the same effect would lead to less filtration, bleeding or segregation.	3.2
Concrete stability	Control	Excessive filtration, bleeding or segregation can lead to irregular flow patterns, and to anomalies.	3.3
Use of additions and (chemical) admixtures	Optimise	Enhances rheology. Might affect robustness and stability of the concrete mix (depending on proportioning and interactions).	4.4
Slump-flow	As per Table 01	Higher values lead to better workability but less stability.	5.1
Slump-flow velocity	As per Table 01	Lower values lead to higher resistance to flow which may increase total pouring time.	5.1
Suitability testing	Laboratory trials at design stage Repeat	Finding suitable composition with available constituents to meet the project specific requirements on concrete, allowing decisions for specifying conformity values. Proving suitability with changes of constituents or dosages.	5.2
Conformity testing	Field trials at start of execution Adapt concrete mix design	Confirming that properties, specified at design stage, can be achieved with the actual concrete from the producer. Allowing conformity with designed performance by small changes in concrete mix design; repeat suitability testing otherwise.	5.2
Identity testing	Frequently during execution	Proving conformity with specifications on a regular basis, and complying with QC regulations.	5.2
Workability retention	Control	Allowing still workable concrete at the end of designed pouring time. An excessive increase in yield stress should be avoided as it may lead to insufficient workability. Longer retention may increase bleeding and segregation.	5.3

TABLE F.1 **VARIOUS FACTORS AND THEIR POSSIBLE EFFECTS ON CONCRETE FLOW AND QUALITY OF DEEP FOUNDATIONS cont.**

PARAMETER	RECOMMENDATION	EFFECT(S)	SEE
Total pour time	Minimise delays	Less change in rheology of the concrete.	5.3
Debris on base	Limit	Debris at the base can contribute to mixing with the initial concrete load and to inclusions.	6.2
Density of support fluid	Limit	Less resistance to concrete flow.	6.2
Cleanliness of support fluid	Maximise	More soil particles in the support fluid may contribute to a thicker interface layer on top of the concrete.	6.2
Tremie pipe surface	Smooth and clean	Limits the friction between concrete and tremie pipe, and the restriction to flow.	6.3
Tremie spacing	Limit	Longer flow distance can cause problems near the reinforcement cage, in the cover zone or near the joints.	6.4 6.8
Tremie embedment	Minimise	Faster concrete flow. Earlier cessation of movement in (finally placed) concrete below the tremie pipe. Reduced risk of dynamic segregation.	6.6
Variations in workability of individual loads	Limit	High variations may lead to a change of flow mechanism, and can contribute to irregular flow patterns.	9

Appendix G

Detailed Information on Numerical Modelling

Appendix G / Detailed Information on Numerical Modelling

This Appendix should be read in conjunction with *Section 9* and includes supplementary information on general aspects, capabilities, validation, demonstrated behaviours and future works, all related to the numerical modelling of tremie concrete flow in a deep foundation.

General aspects

When validated by physical observations, numerical modelling serves as a valuable tool for development of practical recommendations related to tremie concrete properties as well as design and construction practices.

"Numerical tremie models" are digital representations of relevant aspects of the actual tremie method that can include foundation geometry, reinforcement design, mix design and tremie methodology. Numerical tremie models can inform compatibility between foundation design and concrete performance by simulating the casting process in its entirety.

However, due to the computational complexity required to create a comprehensive and complete numerical tremie model, current efforts prioritise scaled or generalised models focussing on improving our understanding of the importance of individual factors, particularly those affecting the flow of the concrete and assessing the sensitivity to changes in factors set out in *Table F.1*.

Scaled or generalised numerical models (refer to *Section 9.3*) typically integrate fluid-based (e.g. Bingham Fluid) simulations with parametric and back-analysis techniques. These techniques are then used to provide insights into potential optimisations of the tremie method.

Capabilities of numerical modelling

It is essential to select an appropriate numerical modelling method when modelling an aspect of the tremie method. Both commercial and bespoke academic approaches have been used to simulate tremie concrete flow and the tremie process, each offering combinations of advantages and disadvantages depending on user requirements.

Second to choosing an appropriate numerical method, is the scale of the simulation. Scale in this instance refers to how much of the entire foundation is simulated. Different aspects of the tremie method require different scales of simulation. For instance, simulations examining the flow around reinforcement cages may require only a portion of the foundation be simulated in high fidelity (lots of cells, points, or elements) whereas bulk flow behaviours may require an entire foundation be simulated but with a lower fidelity. A 1:1 or full-scale simulation in this section refers to a high-fidelity simulation of an entire foundation, a perquisite for creating a complete numerical tremie model.

The table below highlights key capabilities for different common numerical modelling methods that have been used to simulate tremie concrete.

TABLE G.1 **NUMERICAL MODELLING METHOD CAPABILITIES.**

METHOD CAPABILITY	NUMERICAL MODELLING METHOD			
	COMPUTATIONAL FLUID DYNAMICS (CFD)	**FINITE ELEMENT ANALYSIS (FEA)**	**DISCRETE ELEMENT METHOD (DEM)**	**HYBRID LAGRANGIAN / EULERIAN**
Full-Scale Simulations (1:1 Scale foundation has been simulated)	✓*			
Single-Phase (e.g. Concrete is modelled as a Bingham Fluid)	✓	✓		✓
Multi-Phase (e.g. Concrete is modelled as aggregate and fluid)				✓
Granular Representation (Concrete as granular material)			✓	
Multiple Material Models (e.g. Concrete and support fluid modelled separately)	✓	✓		✓
Thixotropic Model** (Concrete can be modelled as a thixotropic fluid)	Partial***	Partial***		✓
'High Deformation' Capable	✓	Partial	✓	✓
Computationally 'Efficient'	✓	✓		

*Simulated with concrete represented as a Bingham model.
**Thixotropy as defined by this Guide.
***By pausing simulations and manually increasing yield stress, a pseudo thixotropy.

Some of the numerical modelling methods described in this section are available commercially, while others are accessible mainly through academic institutions. Several commercial and open-source CFD and FEA packages can readily simulate concrete as a Bingham material. Additionally, some open-source DEM software packages can simulate concrete as a granular material, though these are still undergoing validation, as described in *Section 9.3*. However, few open-source Hybrid Lagrangian/Eulerian methods are available, and their use is likely limited to institutions with significant computational resources.

Validation Methods undertaken

Scaled or generalised models often represent a mathematically idealised version of reality, such as modelling concrete as a Bingham Fluid (a generalised model) or modelling one wedge of an axisymmetric bored pile (a scaled model). These models may neglect certain details for simplicity and ease of use. A validation exercise should be performed to check these simplifications don't significantly alter the model's behaviour compared to reality. Validation helps establish confidence bounds for the model's outputs and defines the range of conditions under which the model can be reliably used.

The most common means of validation is to compare a simulated concrete suitability test (*Section 5.3 Table 2a*) with expected (in the case of slump-flow based on *Section 5.2, Figures 11 and 12*) or observed results. Another common approach involves constructing a specialised laboratory apparatus specifically designed for validation purposes, allowing for a comparison between observed behaviours and simulation results – usually focussing on a few aspects of the tremie method. More complex validation methods, such as large-scale field tests, offer a more comprehensive understanding of the model's behaviour by comparing simulation results against many factors of the tremie method described in Table F.1. Ideally, conclusions about the tremie method should be based on numerical methods with robust and appropriate validation methodologies at the desired scale.

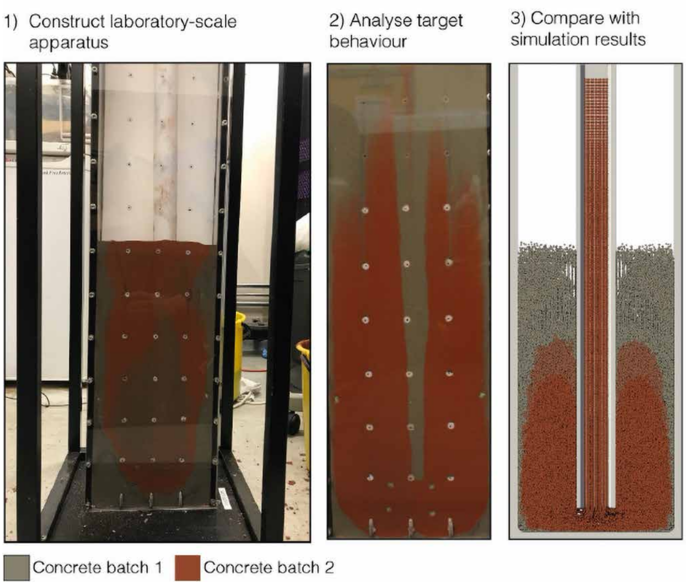
Literature is available for the following methods that have undertaken validation exercises specifically for tremie concrete:

TABLE G.2 **SCALE OF VALIDATION FOR NUMERICAL MODELLING METHODS**

NUMERICAL MODELLING METHOD	SCALE OF VALIDATION COMPLETED				
	CONCRETE WORKABILITY TEST SCALE	CONCRETE STABILITY TEST SCALE	LABORATORY APPARATUS SCALE	PARTIAL FOUNDATION	FULL-SCALE FOUNDATION (1:1)
Computational Fluid Dynamics (CFD)	✓		✓	✓	✓
Finite Element Analysis (FEA)	✓				
Discreate Element Method (DEM)	✓				
Hybrid Lagrangian / Eulerian	✓		✓		

Validation methods should also be considered in the context of the numerical modelling method. For example, CFD validation methods are unable to be validated for use in investigations involving aggregate blocking of reinforcement bars as the model is only able to represent concrete as a single-phase Bingham fluid – rather than aggregate suspended in a fluid matrix (multiphase). It is important to consider both the capabilities of the numerical modelling method and the existing validations together when deciding what method to use.

FIGURE G.1 **AN EXAMPLE OF LABORATORY SCALE APPARATUS VALIDATION IS PROVIDED FROM WILKES 2021, WHERE AN APPARATUS IS CONSTRUCTED, TARGET BEHAVIOUR ANALYSED AND A COMPARISON WITH A SIMULATION MADE.**



Demonstrated Behaviours

The Task Group has worked with Academic Partners to determine fundamental interdependencies and corresponding sensitivities by reviewing model studies. What follows is a short summary of these works.

Flow Patterns

As discussed in *Section 6.7*, fresh concrete flow in deep foundations can be classified by flow patterns, typically referred to as bulging and plug flow. However, recent numerical models have suggested that these tremie concrete flow patterns are not binary (Fierenkothen and Pulsfort, 2017; Fierenkothen, 2019; Wilkes, 2021).

The flow pattern of concrete is likely to be governed by the degree of restriction to flow imposed on the fresh concrete by boundary conditions of the foundation. Most likely, this will be the reinforcement cage. Flow patterns should be considered based on a scale of flow restriction, where low restriction represents an unreinforced foundation and high restriction represents a dense reinforcement cage.

Therefore, during foundation design it is essential to take precautions to prevent creating conditions that could significantly restrict flow by ensuring the recommendations on reinforcement detailing in *Section 2* are adhered to.

Thixotropy

Some thixotropic fresh concrete (as defined by this guide), presented in the review by Kraenkel and Gehlen (2018) discussed in *Section 5*, demonstrates a rapid increase in yield stress over a short period in a rheometer, where yield stress increases significantly during short (minutes) periods of rest.

This large increase in yield stress during rest should correspond to proportionally large reductions in slump-flow, given the relationship between yield stress and slump-flow presented in *Section 5.2, Figure 11*. However, the expected reduction in slump-flow was not observed in the Kraenkel and Gehlen (2018) review. Conversely, numerical models of thixotropic fresh concrete do support the hypothesis that there should be a significant reduction in slump-flow for highly thixotropic concretes after a period of rest (Wilkes, Kumar and Biscontin, 2023). Thus, there is a disparity between the numerical and practical understanding of the risk posed by highly thixotropic concrete undergoing rest periods.

Based on numerical evidence, there may be an increased risk of concrete imperfections occurring when using higher thixotropic concrete, particularly during long periods of intermittence between pours. This is due to an increased restriction to fresh concrete flow caused by the mechanical stiffening of the concrete (Wilkes, 2021).

Until there is confirmation that higher thixotropic concrete behaves in practice as expected by theory, it is recommended that when higher thixotropic concrete is identified (refer to *A.10 Manual Vane Shear Test*) additional precautions are taken to minimise interruptions to concrete discharges. Additional appropriate testing should also be developed to improve understanding of the impact thixotropy has on casting deep foundations.

Mix Variability

Kränkel et al. (2022) performed a series of numerical models of casting bored pile foundations at foundation scale. It was observed that concrete present in the cover zone originated from earlier batches of concrete. It was also observed that if a dense reinforcement cage was present and high-yield stress concrete used as one of these earlier batches, there would be an increase in exposed reinforcement imperfections in the cover zone.

Using conformance, suitability and acceptance testing should ensure each batch of fresh concrete that arrives onsite is within tolerance and fit for purpose. The observations made by Kränkel et al. (2022) support the need for an appropriate fresh concrete testing regime on site to ensure conformance with requirements by highlighting the risk posed by using out-of-specification concrete.

Exposed Reinforcement Imperfections

Vertical and horizontal lines that align with the trace of the reinforcing cage (i.e. "mattressing", as described in *Appendix D*) are assumed to originate during the casting process when fresh concrete cannot flow easily around the reinforcing cage bars.

Kmeid et al. (2024), designed a laboratory apparatus to ascertain how these imperfections originate in diaphragm walls. Fluid dynamics simulations validated against the laboratory apparatus demonstrate that both support fluid properties and fresh concrete rheology influence the ability of concrete to flow around the reinforcement cage bars.

Jeyaraj et al. (2023), using fluid dynamics simulations validated against laboratory scaled apparatus for cast in place piled foundations, also identified that both support fluid and fresh concrete rheology influence the risk of these imperfections occurring. However, it was also suggested that reinforcing cage geometry also plays a significant role in the cause of such imperfections.

According to these scaled and generalised models, restriction to flow (originating from high yield stress concrete, low workability support fluid, and congested reinforcement cages) can lead to exposed reinforcement imperfections. Thus restriction should be minimised where possible by following recommendations in this guide, particularly those about horizonal and vertical spacing in *Section 2.2*.

Recommendations for Future Work

This section summarises key fundamental observations made through experimental and numerical analysis. Continued investment into research of tremie concrete behaviour is required to develop complete numerical tremie models. The Task Group consider the following areas to be the most important:

- Comprehensive understanding of flow behaviours within deep foundations that can inform on retention requirements of fresh concrete.
- Aspects of the tremie method that are governed by best practice recommendations with large degrees of variability, such as tremie embedment depth.
- Aspects of foundation design that are governed by design standards with large degrees of variability, such as reinforcement cage bar spacing.
- Validation methods at full or partial foundation scale.
- Relating observed imperfections to fresh concrete suitability test results – particularly focussed on stability tests.
- Interaction of fresh concrete with other materials involved in the tremie process, e.g. interface materials, support fluids, base debris, and filter-cakes.

References

References

ACI		
ACI CT-13	ACI Concrete Terminology - An ACI Standard	2013
ACI 211.1-91	Standard Practice for Selecting Proportions for Normal, Heavyweight, and Mass Concrete (Reapproved 2009). ACI	1991
ACI 301-16	Specifications for Structural Concrete. ACI	2016
ACI 304R-00	Guide for Measuring, Mixing, Transporting, and Placing Concrete (Reapproved 2009). ACI	2000
ACI 318-14	Building Code Requirements for Structural Concrete and Commentary. ACI	2014
ACI 336.1-01	Specifications for the Construction of Drilled Piers. ACI	2001
ACI 336.3R-14	Report on Design and Construction of Drilled Piers. ACI	2014
ACI 350-06	Code Requirements for Environmental Engineering Concrete Structures. ACI	2006
ACI 543R-12	Guide to Design, Manufacture, and Installation of Concrete Piles. ACI	2012

ASTM INTERNATIONAL		
ASTM C143-15	Standard Test Method for Slump of Hydraulic-Cement Concrete. ASTM Standard	2015
ASTM C232-14	Standard Test Method for Bleeding of Concrete. ASTM Standard	2014
ASTM C1602-12	Standard Specification for Mixing Water Used in the Production of Hydraulic Cement Concrete. ASTM Standard	2012
ASTM C1610-14	Standard Test Method for Static Segregation of Self-Consolidating Concrete Using Column Technique. ASTM Standard	2014
ASTM C1611-14	Standard Test Method for Slump Flow of Self-Consolidating Concrete. ASTM Standard	2014
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