AS 8700—2011

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Australian Standard®

Execution of prefabricated vertical drains

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Execution of prefabricated vertical drains

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PREFACE

This Standard was prepared by Standards Australia Committee CE-020 Geosynthetics, in response to requests from industry representatives in the field of prefabricated vertical drains, especially in the area of land reclamation.

This Standard is based on BS EN 15237, *Execution of special works. Vertical drainage.*

The objective of this Standard is to establish general principles for the execution, testing, supervision and monitoring of prefabricated vertical drains.

This Standard expands on design only where necessary, but provides full coverage of the construction and supervision requirements.

The terms 'normative' and 'informative' have been used in this Standard to define the application of the appendix to which they apply. A 'normative' appendix is an integral part of a Standard, whereas an 'informative' appendix is only for information and guidance.

Numbers set within parentheses refer to documents referred to during the preparation of this Standard. These references are listed in the Bibliography.

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STANDARDS AUSTRALIA

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Execution of prefabricated vertical drains

SECTION 1 SCOPE AND GENERAL

1.1 SCOPE

This Standard provides general requirements for the execution, testing, supervision, monitoring and installation methods of prefabricated vertical drain projects. It also includes information on design considerations, and practical and design aspects of vertical drainage.

Prefabricated vertical drains are used for the improvement of low-permeability, highly compressible soils, and in on-land and marine constructions for—

(a) (pre)consolidation and reduction of post-construction settlements; speeding up the consolidation process by decreasing the path lengths for pore water dissipation;

(b) increasing soil stability (by increasing effective stresses in the soil);

(c) groundwater lowering; and

(d) mitigation of liquefaction effects.

In each case there is an overall treatment of the soil (the volume of the drains is small in relation to the soil volume treated).

Prefabricated vertical drains may also be combined with other foundation or ground improvement methods (e.g. sand drains, vacuum consolidation, electro-osmosis, piles and compacted sand piles, rigid inclusions, dynamic compaction and deep mixing).

NOTES:

1 See References 1, 2, 3 and 4 in the Bibliography.

2 Guidance on practical aspects of prefabricated vertical drains, such as investigation of drain properties, execution procedures and equipment, is given in Appendix A.

3 Guidance on the evaluation of soil characteristics and design considerations is given in Appendix B.

1.2 NORMATIVE REFERENCES

The following are normative documents referenced in this Standard:

NOTE: Documents referenced for informative purposes, including material referred to during the preparation of this Standard, are listed in the Bibliography.

AS		
1726	Geotechnical site investigations	
2001	Methods of test for textiles	
2001.2.15	Part 2.15:	Physical tests—Determination of thickness of textile fabrics
2001.2.3.2	Part 2.3.2:	Physical tests—Determination of maximum force using grab method (ISO 13934-2:1999, MOD)

AS

3706 Geotextiles

3706.2 Part 2: Methods of test—Determination of tensile properties—Wide-strip method

3706.6 Part 6: Methods of test—Determination of seam strength

3706.7 Part 7: Methods of test—Determination of pore-size distribution—Dry-sieving method

3706.9 Part 9: Methods of test—Determination of permittivity, permeability and flow rate

ASTM

D4716 Standard Test Method for Determining the (In-plane) Flow Rate per Unit Width and Hydraulic Transmissivity of a Geosynthetic Using a Constant Head

EN ISO

12958 Geotextiles and geotextile-related products—Determination of water flow capacity in their plane

ISO

12117-2 Earth-moving machinery—Laboratory tests and performance requirements for protective structures of excavators

Part 2: Roll-over protective structures (ROPS) for excavators of over 6 t

1.3 DEFINITIONS

For the purposes of this document, the definitions below apply.

1.3.1 Auger installation method

Installation method by means of a screw type auger or continuous flight hollow stem auger to prebore stiff/dense soils.

1.3.2 Discharge capacity (q_w)

The cross-sectional area of the drain multiplied by its overall permeability in longitudinal direction (the volume of water that flows out of the drain per time unit under a hydraulic gradient equal to unity).

1.3.3 Displacement installation method

Installation method of drains by means of a hollow tube with end closed off with an anchor plate.

1.3.4 Drain anchor plate

Anchor plate fixed at the end of prefabricated vertical drains before installation, which prevents soil from intruding into the mandrel during installation and the drain from being dragged up when the mandrel is withdrawn.

1.3.5 Drainage blanket

Upper high-permeability drainage layer, which has good contact with the drains, prevents the creation of backpressure in the drains and facilitates egress from the soils.

1.3.6 Dynamic installation method

Drain installation method using dynamic action (impact or vibratory hammer).

1.3.7 Mandrel

Open steel tube used to push the drain below ground.

NOTE: The drain is located inside the mandrel and attached to an anchor plate at the base of the mandrel. Mandrel, with the drain inside, is pushed to the design depth or until a firm layer is encountered. Then the mandrel is withdrawn leaving the drain and the anchor in place. Generally mandrels have a cross-sectioned area of 6000 mm2 to 8000 mm2 and 8 to 10 mm wall thickness.

1.3.8 Prefabricated vertical drain (PVD)—Wick drain

1 A prefabricated drain with a rectangular cross-section, usually consisting of a central core with a channel system surrounded by a filter sleeve (commonly known as a flat drain).

2 A prefabricated drain consisting of an annular-corrugated and perforated open circular core, surrounded by a filter sock, commonly known as a round drain.

1.3.9 Static installation method

Drain installation method by means of static load (pushing).

NOTE: This is the most commonly used method.

1.3.10 Vibro installation method

Installation method of drains by means of a top vibrator mounted on a hollow mandrel or by a depth vibrator.

1.3.11 Working platform

Platform created for access and support of the drain installation machines to the treatment area.

1.4 NOTATION

Symbol		Definition
A	=	area
a	=	width of the prefabricated flat drain
a_v	=	coefficient of compressibility of soil
b	=	thickness of the prefabricated flat drain
c_h	=	coefficient of consolidation for horizontal drainage
c_v	=	coefficient of consolidation for vertical drainage
D	=	diameter of influence zone
D_{15}	=	diameter of soil particles corresponding to 15% passing
D_{50}	=	diameter of soil particles corresponding to 50% passing
D_{85}	=	diameter of soil particles corresponding to 85% passing
d_m	=	diameter of mandrel
d_s	=	diameter of smear zone
d_w	=	diameter of drain
e	=	void ratio
f_{cr}	=	creep factor
k_{filter}	=	permeability coefficient of filter
k_h	=	horizontal permeability coefficient in undisturbed zone

k_s = horizontal permeability coefficient in smear zone

k_{soil} = permeability coefficient in soil

k_v = vertical permeability coefficient

k_w = drain permeability coefficient

l = length of the drain

O_{90} = apparent opening size

O_{95} = equivalent opening size

O_{50} = apparent opening size

q_p = in-plane flow capacity

q_w = discharge capacity of drain

R = radius of influence zone

r = radial distance from centre

S = drain spacing

t = consolidation time

T_h = dimensionless time factor for horizontal drainage

T_v = dimensionless time factor for vertical drainage

$\bar{U}_h$ = average degree of horizontal consolidation

U_t = required degree of consolidation

U_v = degree of consolidation for vertical drainage

u = excess pore pressure

z = depth

γ_w = unit weight of water

1.5 INFORMATION REQUIRED BEFORE THE EXECUTION OF THE WORK

1.5.1 General

Prior to the execution of the work, all necessary information shall be available.

1.5.2 General information required

The following are required:

(a) Relevant information regarding the site conditions.

(b) The location of main grid lines for setting out.

(c) Design and construction drawings with the location and length of the drains.

(d) Any legal or statutory restrictions.

(e) Method statement for the vertical drain installation (see Clause 4.1).

(f) Characteristics of the drains (physical and hydraulic characteristics).

(g) Specification for the drains and other materials to be used (see Section 2) and the schedule of any testing and acceptance procedures for materials incorporated in the works.

(h) Description of a suitable quality management system, including supervision and monitoring.

1.5.3 Information on site conditions

1.5.3.1 *General*

The information for the site conditions shall be documented. Where relevant, the documentation shall cover the following:

(a) The geometry of the site (boundary conditions, topography, access, slopes, headroom restrictions, etc.).

(b) The ground properties of the site that may influence the execution of the vertical drains (see Clause 1.5.3.2), that is—

  (i) soil description (soil type, soil stratification and existence and frequency of sand and silt layers, hard layers);

  (ii) penetration resistance (e.g. results of penetration tests);

  (iii) composition, lateral extent, thickness and firmness of the surface stratum, tree roots, fill; and

  (iv) presence of cobbles or boulders or cemented layers that can cause difficulties for the execution or could require special installation equipment.

(c) The following climatic and environmental information:

  (i) Weather information in areas with extreme climatic conditions.

  (ii) Marine conditions (currents, tidal movements, wave heights, etc.).

  (iii) Environmental hazards (any water and subsoil contamination or acid sulfate potential that could affect the execution method, the safety of the work or the discharge of excavation material from the site, including the presence of hazardous gas and the rare but possible occurrence of unexploded ammunition).

(d) The existing underground structures, services, known contamination and archaeological constraints.

(e) The environmental restrictions, including noise, vibration, for dynamic installation method and use of mandrel (see Clauses 1.3.7 and 1.3.10) and pollution.

(f) Planned or ongoing construction activities, such as dewatering, tunnelling and deep excavations.

(g) Previous experience from drain installation work adjacent to the site.

(h) The characteristics of the working platform and the drainage layer (physical and hydraulic properties).

(i) The conditions of structures, roads and services adjacent to the work.

1.5.3.2 *Geotechnical investigations*

The geotechnical investigations carried out for the design of prefabricated vertical drainage work shall be in accordance with the requirements of AS 1726 and provide information for the installation of the vertical drains [see Clause 1.5.3.1(b)].

The geotechnical investigation report shall be available in sufficient time to allow for planning, design and execution of the vertical drainage works.

Apart from the general geological description and the details listed in AS 1726, the site investigation report shall contain information regarding ground conditions for the execution of vertical drain installations and for loading.

NOTES:

1 For information on the practical aspects to be taken into consideration for vertical drainage, see Appendix A.

2 For information on aspects of design, see Appendix B.

Information about ground conditions shall also include the following:

(a) Piezometric levels of groundwater, its variation and possible deviation from hydrostatic pressure conditions.

(b) Undrained shear strength.

(c) The ground level and location at any point of investigation, which shall be established relative to the recognized national datum or to a fixed reference point.

1.5.4 Information for the loading operation

For the loading operation, the following design and construction information shall be available:

(a) Program for loading.

(b) Preloading (temporary and permanent loading).

(c) Time schedule for loading and possible preloading.

(d) Unit weight of fill used for preloading.

(e) Current and post construction/long-term groundwater levels.

(f) Notice of any restrictions such as construction phasing required in the design.

(g) Monitoring program.

1.5.5 Reporting procedures

The following procedures shall also be given:

(a) Reporting procedure for unforeseen circumstances, or conditions revealed that appear to be different from those assumed in the design.

(b) Reporting procedure, if an observational method of design is adopted.

SECTION 2 MATERIALS AND PRODUCT

2.1 TESTING STANDARDS FOR SPECIFIC MATERIAL PROPERTIES

All properties listed in Table 2.1 shall be tested according to at least one nominated Standard, and shall be documented by the manufacturer/supplier of prefabricated vertical drains shown in Table 2.1.

NOTE: It is recommended that Australian Standards be used when available for any property to be assessed unless circumstances dictate equivalent Standards to be adopted.

TABLE 2.1

SPECIFIC STANDARDS USED FOR THE TESTING AND DETERMINATION OF PROPERTIES OF PREFABRICATED VERTICAL DRAINS

Property to be tested	Applicable Standard
Maximum tensile force, in kilonewtons (kN)	AS 3706.2
Elongation at maximum tensile force, in percent (%)	AS 3706.2
Tensile strength of filter, in kilonewtons per metre (kN/m)	AS 3706.2
Tensile strength of seams and joints, in kilonewtons per metre (kN/m)	AS 3706.6
Grab tensile strength, whole drain	AS 2001.2.3.2
Grab tensile strength, filter	AS 2001.2.3.2
Permittivity/permeability, in millimetres per second (mm/s)	AS 3706.9
Pore size of filter (O_{90} or O_{95}), in micrometres (µm)	AS 3706.7
Discharge capacity of the drain, in cubic metres per year (m^3/year)	EN ISO 12958 or ASTM D4716 (see also Appendix A)
Thickness, in millimetres (mm)	AS 2001.2.15

NOTES:

1 It is acknowledged various ISO and ASTM standards exist that are equivalent to Australian Standard test methods. Appendix D lists the common methods.

2 The tensile strength tests tabled above are based on a 200 mm wide standard specimen. For these drains and the filter, a 200 mm wide specimen may not be possible in which case the test shall be conducted on the available width of specimen and a note to that effect shall be included in the results.

2.2 RAW MATERIALS OF PREFABRICATED DRAINS

A prefabricated drain comprises a synthetic polymer, typically synthetic polypropylene, polyethylene polyester or polyvinyl chloride and is used in applications in soils with a pH-value between 4 and 9 and at a soil temperature less than 25°C. A service lifetime of up to 5 years is applicable.

NOTE: For longer term applications, reference should be made to HB 154 where additional testing may be required to confirm longer term durability and further durability tests may need to be undertaken.

The use of up to 10% internal regenerate (e.g. raw material made out of unused core) for the production of the core is permitted. The composition shall be known and the material shall be processed in the same way as the original product. Recycled material may be used provided it can be verified that it is not causing pollution of the soil or groundwater.

Any additional or deviating requirements shall be established and agreed upon prior to the commencement of the works.

Materials used to manufacture the drains shall not cause pollution of the soil or the groundwater.

2.3 FLAT DRAINS

2.3.1 Shape and structure of flat drain

The flat drain is a prefabricated drain with a rectangular cross-section, usually consisting of a central core with a channel system surrounded by a filter. The width of the core of the flat drains is typically 100 mm and the thickness is between 2 mm and 5 mm.

The core shall consist of a profiled strip, with or without perforation, or a profiled mat with an open or closed structure. It shall have a structure that provides uniform hydraulic flow capacity.

Tears and/or other defects shall not be allowed to occur. Visual inspections for damage shall be made regularly as part of the production quality control.

2.3.2 Measurements

The roll length, width and thickness of the core of the flat, at any given place, shall comply with the dimensions given by the manufacturer (within allowable deviations given by the manufacturer) as part of quality control information.

2.3.3 Durability

The drain shall be protected against weathering during storage on the site.

The product shall not be exposed longer than the time nominated by the manufacturer unless the product is protected by a wrapping material or stored in-house. The recommendations of the supplier shall be followed.

2.3.4 Tensile strength and elongation

The required tensile strength of the flat drain is dependent upon the type of installation machine, installation technique and depth of the drain. Tensile strength of the flat drains in the longitudinal direction shall be high enough to prevent breakage during and after installation.

Testing of tensile strength and elongation of the flat drain shall be made in accordance with the relevant Standards listed in Table 2.1 (modified with regard to the width of the product).

NOTE: The following characteristics of a flat drain are recommended:

(a) Elongation ≥2% at failure of the weakest element.

(b) Elongation ≤10% at a tensile force of 0.5 kN (20% if exposed to frost).

(c) Minimum tensile strength of 7 kN/m at failure of the complete drain, modified with regard to the actual width of the product test specimen.

The strength of the seam, measured according to the relevant Standards in Table 2.1 in a range of temperatures that apply to the project site, shall be at least 1 kN/m.

The grab tensile strength shall be greater than 1.6 kN for the composite drain and 0.3 kN for the filter.

2.3.5 Discharge capacity

The discharge capacity and the filtration characteristics are the most important properties. The following factors influence the discharge capacity:

(a) Due to increasing lateral effective pressure during the consolidation process, the filter is squeezed into the channel system of the core, which reduces the channel area.

(b) The vertical compression of the soil that takes place during the consolidation process may lead to buckling of the relatively incompressible flat drains, which may reduce the discharge capacity.

(c) Fines may intrude through the filter into the core and cause blocking of the channel system.

(d) Soil temperature has an influence on the compression resistance and creep of the drains and thus on the discharge capacity.

The required discharge capacity of the flat drain is largely dependent upon the purpose of ground improvement, the consolidation parameters of the soil, the drain spacing and the depth of drain installation (see Note 1).

The discharge capacity shall be high enough to satisfy the design requirements (see Note 2).

The discharge capacity test shall be carried out in accordance with the relevant Standards listed in Table 2.1 and with the appropriate modifications (see Note 3).

For usual applications, the discharge capacity test shall be performed at the laboratory temperature and then the test report shall be referred to a temperature of 20°C. For applications in tropical environment, the discharge capacity test shall be performed at a temperature corresponding to the soil temperature at the place of drain installation and then the test report shall be referred to that specific temperature.

The test period shall be long enough to yield a constant value of discharge capacity; preferably at least two days at the maximum static pressure stipulated by the designer.

NOTES:

1 For design aspects, see Appendix B.

2 The recommended value of the discharge capacity is given in Appendix B.

3 For recommended modification, see Appendix A.

2.3.6 Filter of flat drains

The filter sleeve of the flat drain shall be composed of a non-woven material consisting of fibres that are mechanically, chemically or thermally bonded.

The occurrence of creases, tears, holes and/or other defects shall not be allowed. The seams of the filter sleeve shall be constructed in such a way that fines cannot intrude into the core of the flat drain.

Visual inspections for damage shall be made regularly during production in accordance with the factory production control plan.

2.3.7 Tensile strength per unit width of filter

The tensile strength of the filter shall be sufficient to prevent breakage during and after installation.

Testing shall be carried out in accordance with the relevant Standards listed in Table 2.1. The average of the individually measured values for the tensile strength shall be not lower than 7 kN/m in the longitudinal direction.

2.3.8 Permittivity/permeability of filter

Testing shall be carried out in accordance with the relevant Standards listed in Table 2.1. The average of the individually measured values shall comply with the recommended average values. In case of drain installation for liquefaction problems, the filter pore size shall be adapted to ensure adequate permeability of the filter for this application.

2.3.9 Pore size of filter

The pore size of filter shall be selected to ensure sufficient discharge capacity and avoid serious loss of discharge capacity due to clogging of the filter and/or the core by soil particles. The seams of the filter shall not have an opening size larger than that of the geotextile filter.

Primarily, the requirements for the filter sleeve characteristics shall be given in the project, considering the soil properties at the site and the installation conditions (dry or wetland, offshore).

The value of the pore size O_{95} shall be not greater than 80 µm.

NOTES:

1 The value of O_{95} may be influenced by project-specific requirements and higher values may be acceptable.

2 Some guidance on filter selection is provided in Paragraph B4.2.1, Appendix B.

2.3.10 Quality control

The flat drain shall comply with this Standard and the conformity assessment procedures that apply to it.

The on-site testing frequency shall be decided between the parties involved.

NOTE: The filter and drain characteristics and corresponding testing methods, as well as the proposed testing frequency, are given in Table 2.2.

TABLE 2.2

PROPOSED TESTING FREQUENCY FOR FABRICATION CONTROL

Property	Proposed test frequency	Required Standard
Filter		
Thickness	25 000 m^2	AS 2001.2.15
Mass per unit area	25 000 m^2	AS 2001.2.13
Pore size	500 000 m^2	AS 3706.7
Permittivity/Permeability	200 000 m^2	AS 3706.9
Tensile strength in the longitudinal direction	200 000 m^2	AS 3706.2
Tensile strength in the cross-direction	200 000 m^2	AS 3706.2
Tensile strength of filter seam	500 000 m	AS 3706.6
Grab tensile strength	500 000 m	AS 2001.2.3.2
Drain composite		
Width and thickness	25 000 m	AS 2001.2.15
Mass per unit length	25 000 m	AS 2001.2.13
Tensile strength in the longitudinal direction	100 000 m	AS 3706.2
Grab tensile strength	500 000 m	ASTM D4632, ISO 13934-2, AS 2001.2.3.2
Elongation at maximum tensile force	100 000 m	AS 3706.2
Discharge capacity straight	500 000 m	(see Note)
Discharge capacity buckled	500 000 m	(see Note)

NOTES:

1 Guidance for testing for discharge capacity is given in Appendix A.

2 The tensile strength tests tabled above are based on a 200 mm wide standard specimen. For these drains and the filter, a 200 mm wide specimen may not be possible in which case the test may be conducted on the available width of specimen and a note to that effect should be included in the results.

3 It is acknowledged that various ISO and ASTM Standards are equivalent to Australian Standard test methods. Appendix D lists common test methods.

2.3.11 Delivery quality assurance

The need for on-site verification should be agreed by the parties involved, in consideration of the risks and the scale of the project.

Should on-site testing be deemed necessary, Table 2.3 provides guidance on the frequency for delivery or on-site testing.

TABLE 2.3

PROPOSED TESTING FREQUENCY FOR DELIVERY QUALITY ASSURANCE

Property	Proposed test frequency
Filter	
Mass per unit area	100 000 m^2
Permittivity/Permeability	100 000 m^2
Tensile strength in the longitudinal direction	100 000 m^2
Drain composite	
Width and thickness	100 000 m
Mass per unit length	100 000 m
Tensile strength in the longitudinal direction	100 000 m
Elongation at maximum tensile force	100 000 m

2.4 PREFABRICATED ROUND DRAIN

2.4.1 Shape and structure of round drain

A round drain consists of an annular-corrugated and perforated open circular core, surrounded by a filter sock. The drain diameter is typically 30 mm to 50 mm in outer diameter and 5 mm in wall thickness.

Tears and/or other defects shall not be allowed to occur in a round drain. Visual inspections for damage shall be made regularly as part of the production quality control.

2.4.2 Measurements

The diameter and thickness of the core shall comply with the dimensions given by the manufacturer (within allowable deviations given by the manufacturer).

2.4.3 Durability

The durability requirements for round drains shall be in accordance with Clause 2.3.3.

2.4.4 Tensile strength and elongation

The required tensile strength of the round drain is dependent upon the type of installation machine, installation technique and depth of the drain.

Tensile strength of the drain in the longitudinal direction shall be high enough to prevent breakage during and after installation.

Testing of tensile strength and elongation of the round drain shall be made in accordance with the standard tensile test with modified clamps (see Table 2.1).

The strength of the seam, measured according to the relevant Standards listed in Table 2.1 (with modified clamps) in a range of temperatures that apply to the project site, shall be at least 1 kN/m.

The grab tensile strength of the filter shall be greater than 0.3 kN.

2.4.5 Discharge capacity and filtration characteristics

The discharge capacity of the round drains is usually much larger than is required for soil consolidation. It may decrease if the round core is crushed due to an increase of lateral effective pressure during the consolidation process and/or buckling.

The perforation of the pipe (core) shall not be sealed due to compression of the filter sleeve.

The pipe and filter of drains used for longer term applications shall consider longer term durability aspects (see Clause 2.2).

2.4.6 Filter of round drain

The fitter of round drains shall comply with the requirements of Clause 2.3.6.

2.4.7 Tensile strength per unit width of filter

The tensile strength per unit width of filter for round drains shall comply with the requirements of Clause 2.3.7.

2.4.8 Permittivity/permeability of filter

The permittivity/permeability of the filter of round drains shall comply with the requirements of Clause 2.3.8.

2.4.9 Pore size of filter

The pore size of filter for round drains shall comply with the requirements of Clause 2.3.9.

2.4.10 Quality control

The round drain shall comply with this Standard and the applicable conformity assessment procedures.

NOTE: The filter and drain characteristics and corresponding test methods, as well as the testing frequency, are given in Table 2.2, except that the discharge capacity tests (straight and buckled) need not apply.

SECTION 3 DESIGN CONSIDERATIONS

3.1 GENERAL

The scope of the application of vertical drainage is to handle and solve problems associated with the following aspects of geotechnical engineering:

(a) Consolidation settlement in low-permeability soils (resulting from surface loading or groundwater lowering).

(b) Stability (of structures and embankments).

Other applications of vertical drainage include treating soils exposed to the effects of dynamic and cyclic loading (e.g. in seismic regions or under rail tracks), as a result, the impacts of which can be reduced as well as the effects of vibrations on structures reduced. Vertical drainage may also be used for remediation of contaminated ground and for mitigation of liquefaction potential.

Vertical drainage design encompasses two phases, as follows:

(i) *Functional design* Functional design is the first phase and the need for vertical drainage has to be quantified. This phase defines the loading and drain spacing necessary to produce the desired effects on rate of consolidation and settlements. Treatment of soft soils with vertical drainage followed by preloading provides ground improvement by accelerated consolidation resulting in gain in the undrained shear strength of the soil. It results in a reduction, post-development, of in-service settlements under design loads and also in creating satisfactory drainage paths for pore water in the case of liquefaction.

(ii) *Process design* Is the second phase, the method of drain installation and its functioning in practice has to be designed. This phase accounts for effects of drain installation on the ground, geometry, the nature and the dimensions of the drains and for effects such as possible buckling in case of excessive strains in some soil layers.

3.2 DESIGN PHILOSOPHY

Vertical drainage may be used for different purposes as outlined in Clause 3.1; however, the process of designing vertical drainage generally follows the operations listed in Figure 3.1. The objective (design basis) and the ground properties (first row of boxes) interact with the settlement and stability analyses to satisfy the requirements put on the targeted outcome from the effect of the drains; that is to reach a given degree of global and/or local consolidation within a specific period of time.

Ground treatment by vertical drainage and the associated subsequent preloading shall be designed and executed in such a manner that the structure, embankment or paved area supported by the treated ground, during its intended life and with an appropriate degree of reliability and cost-effectiveness, will remain fit for the intended use and sustain all actions and influences that are likely to occur.

The serviceability requirements for the development of the soft soil site shall be specified by the client. The observational method, which involves adapting the design in a planned manner, is an important part of the design.

The design shall take into account the loads that could occur during construction and service. It shall account for the known effect of the drain installation on the properties of the ground and the effects of the initial and longer term groundwater levels and the impacts such levels may pose on the preloading design.

The installation of vertical drains may also induce excess pore water pressure creating a short-term reduction of the undrained shear strength.

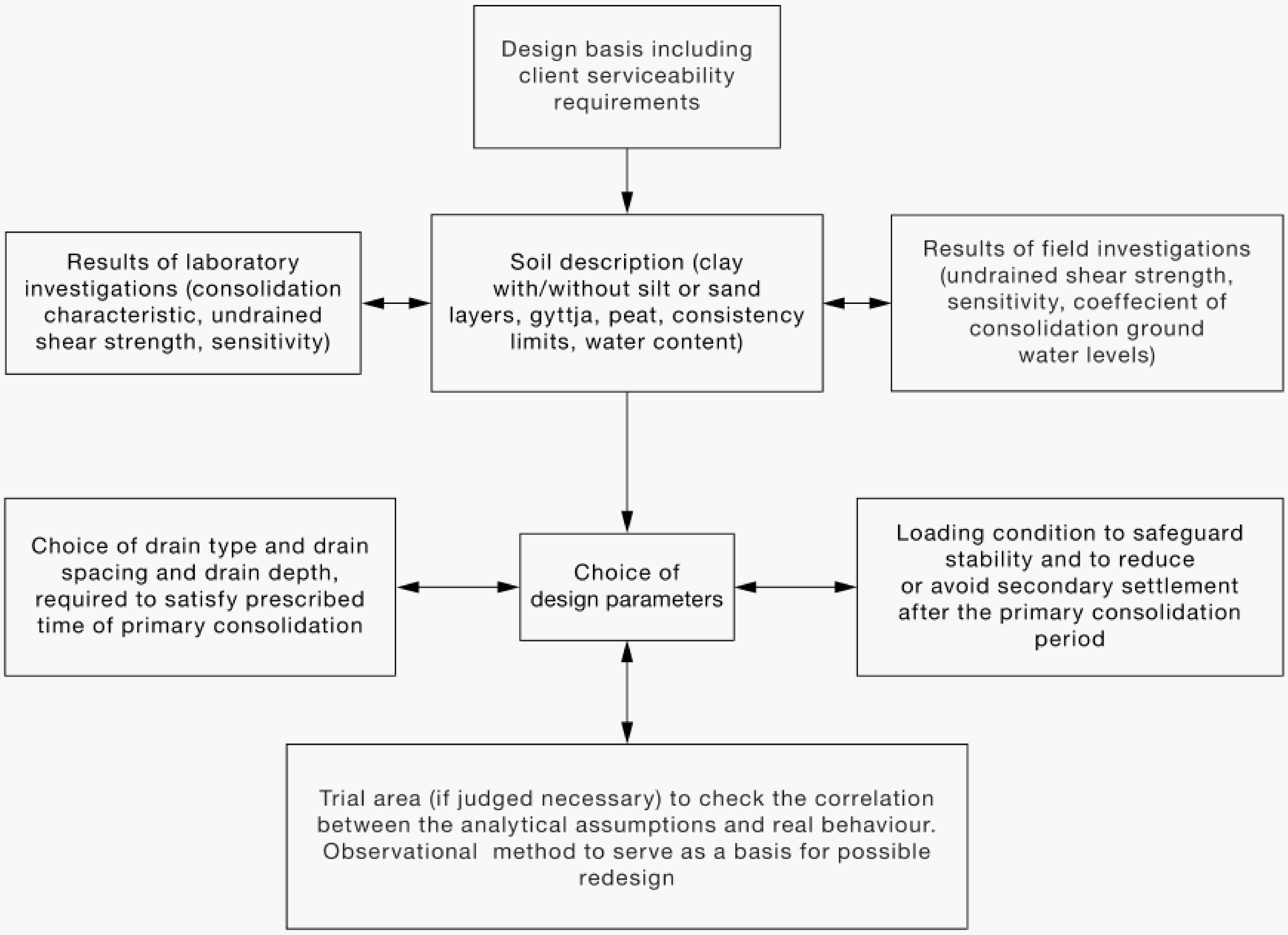


FIGURE 3.1 CHART OF DESIGN PROCESS, INCLUDING LABORATORY AND FIELD INVESTIGATIONS, FUNCTIONAL DESIGN AND FIELD TRIALS

The design shall consider the following:

(a) *Subsurface characterization* Generally using field and laboratory investigations, special attention shall be given to assess the preconsolidation stress, drainage boundary conditions and the consolidation characteristics of the soils.

NOTE: It may be worthwhile to carry out trials at an early stage to assess the performance of PVDs and the soils.

(b) *Developed land use and associated loadings* Account shall be taken of the final ground level after development and the long-term loading conditions.

(c) *Current and future groundwater levels* The groundwater level is essential to determine the effective stress of the soils at the current state as well as in the future. Special attention shall be given to the groundwater level if it is located within or intrudes into the fill placed for preloading operations.

(d) *Acceptable in-service settlements* While the acceptable in-service settlement has to be ultimately the decision of the client, geotechnical consultants may be needed to advise on the consequences and the related risks. For example, the client may accept a higher settlement for a road if the expected differential settlement and grade are small with low risk for traffic, saving vertical drainage costs.

(e) *Required soil strength improvement to address stability* Stability during considerations may drive the designer to aim for quicker rate of dissipation by reducing drain spacing because of related quicker strength gain, or look at applications such as vacuum consolidation or other types of ground improvement.

(f) *Site constraints* The designer shall consider the space limitations as well as the effects on adjacent properties. Access to site and drainage are also important considerations.

(g) *Economy* While the client will ultimately decide whether to accept recommendations of the designer, the latter needs to advise the client why the design was selected, its basis and cost effectiveness.

(h) *Installation* Effects of installation, including smear effects, shall be considered in the design.

(i) *Instrumentation and monitoring* Instrumentation shall be used to assess the performance and, if necessary, take remedial measures. This forms an important tool in any observational method adopted and the benefits shall be clearly discussed with the client.

NOTES:

1 Appendix B describes additional considerations of the design process and other aspects of design in greater depth.

2 Appendix A provides details on practical aspects of installation, preloading and performance monitoring.

3.3 FIELD TRIALS

Test areas with various drain spacing and/or various drain types may be required as a basis for the final design of the drain installation work in order to optimize and demonstrate cost and time benefits.

NOTE: See Ref. 5 in the Bibliography.

The process of consolidation in the test areas shall be monitored by settlement measurement in combination with pore pressure measurement.

NOTE: The preferred means are settlement gauges and piezometers placed at various depths.

The strength increase due to consolidation may be assessed by laboratory tests and/or in situ tests.

Where relevant, the horizontal displacements along the periphery of the test area may be measured by means of an inclinometer.

For test areas with partially penetrating drains, the influence on the consolidation process of underlying untreated soil layers shall be taken into account.

SECTION 4 EXECUTION

4.1 METHOD STATEMENT

A method statement shall be prepared. The method statement shall detail the location, drain grid/pattern, equipment and method of installation, possible restrictions during the construction phase and any hazards associated with the execution of the work.

The equipment and installation method chosen by the contractor shall be assessed and approved.

The method statement shall include, as a minimum, the following (see Clause 1.5):

(a) Objective and scope of drain installation.

(b) Site installation and working areas.

(c) Plant and equipment.

(d) Control procedures.

(e) Procedures regarding possible interruptions during drain installation and/or preloading.

(f) Calibration/verification testing methods.

(g) Working documents (layout, drawings, reports).

(h) Measures to avoid puncturing of artesian groundwater.

(i) Safety and environmental risk assessment.

If judged necessary, trial installations shall be carried out to confirm the suitability of the installation machine for the site conditions.

4.2 PREPARATION OF THE SITE

The preparation shall be carried out in accordance with the design specifications and the specific site conditions. This shall include suitable access for plant and machinery, levelling of the working platform, providing adequate ground-bearing capacity for equipment and installation of a drainage blanket. The requirements for a working platform adequate for installation machines shall be assessed prior to construction (see Clause 1.5.3.1). It may be economical in certain instances to increase the thickness of the drainage blanket instead of importing different working platform material. Subject to ground conditions, the thickness of the working platform may vary widely.

All materials and products for vertical drainage delivered to the site shall be identified and checked against the materials and products specifications in addition to providing the client's representative with a sample.

The drainage blanket shall be at least 0.3 m thick. It shall consist of gravelly sand, sandy gravel or sand containing less than 5% of material with grain size <0.06 mm (see Note).

It shall be protected from ingress of fine-grained material and frost that can detrimentally affect its permeability. It may also consist of an appropriate draining system of geotextile or geotextile-related products.

NOTE: The maximum size of material be less than 75 mm.

When the drainage blanket consists of a layer of granular material, instructions shall be given regarding the methods and frequency of checking the grain size distribution and permeability of the drainage blanket material.

In situ sampler of the drainage blanket materials shall be tested at a frequency nominated by the designer, not less than 1 per 1000 m^3 or 1 per site.

4.3 DRAIN INSTALLATION

The surface location of installation of each drain shall deviate less than 0.15 m from the specified location. The verticality of the installation machine shall be not less than 50 (vertical):1 (horizontal), unless obstructions make it impossible.

Where it is impossible to install a drain as a result of obstructions, another drain shall be installed as close as possible.

If the presence of fill or dense soil at the surface makes installation of drains by conventional methods difficult, hard layers shall be penetrated by pre-augering, or other appropriate methods, prior to drain installation.

Drains shall be installed to the depth specified in the design (within a tolerance of 0.15 m). In soft soil deposits with varying thickness, this depth may be defined as that of the underlying less compressible more resistant layer.

Underlying layers with greater resistance may be identified by a sudden increase in the recorded resistance of the mandrel penetration and may be cross-referenced against existing field investigation results.

Where the drain is unable to be anchored at the design depth due to very low soil resistance, a new drain shall be reinstalled to a greater depth to facilitate anchoring immediately adjacent to the original location.

For drain installation, the mandrel shall leave a free inside space for the drain and shall be constructed in a way to limit soil disturbance.

NOTE: Further information is given in Appendix A.

The installation machine for drains shall be provided with a fully automatic data recorder. The following parameters shall be recorded:

(a) Drain identification number.

(b) Date and time.

(c) Depth of installation and penetration resistance/variation with depth.

(d) Accumulated amount of installed drain length.

(e) Verticality and location.

Splicing of drains is permitted, provided the drainage path is not obstructed and the tensile strength of the splice complies with the requirements of the relevant Standards listed in Table 2.1.

4.4 SPECIAL ASPECTS

The method of drain installation shall not threaten the site stability. In particular, attention shall be paid to excess pore water pressure being built up during the installation process by dynamic methods, and in strain-sensitive clays (quick clays) by displacement methods.

Before drains are installed into the soil, they shall be provided with an anchor that keeps the drain in place when the mandrel is withdrawn from the soil. The soil shall be prevented from intruding into the mandrel during installation.

NOTE: See Paragraph A4.1.3, Appendix A, for installation methods.

After the mandrel is withdrawn, the drains shall be cut so that the drains are in adequate hydraulic connection with the drainage blanket; preferably 0.25 m above the surface of the working platform. Round drains shall be folded down to prevent intrusion of soil particles that may inhibit the drain performance.

For fully penetrating drains connected to a lower high-permeability layer, the penetration into this layer shall be sufficient to ensure that the drains are in adequate hydraulic connection with it.

SECTION 5 SUPERVISION, MONITORING AND RECORDS

5.1 SUPERVISION

In order to check that construction complies with the design and other contract documents, suitably qualified personnel, experienced in the technique, shall be in charge of supervising the execution work.

Where unforeseen conditions are encountered or new information about ground conditions become available, they shall be reported immediately to those responsible for the design.

The specific procedures for verification, control and acceptance shall be established before the commencement of the work. This shall include trial installations adjacent to geotechnical test locations where soil profile is known.

The actual frequency and method of control shall be stated.

Identification of prefabricated vertical drains shall be carried out on site and, as a minimum, the roll number, product grade and product name shall be provided.

5.2 MONITORING

The extent and procedures of monitoring shall be specified by the design.

The extent of the monitoring system shall account for the type of loading (e.g. step-wise loading, vacuum, groundwater lowering), for the choice of drain type and for previous experience of results achieved under similar soil and loading conditions and with similar types of drains.

The construction process shall be controlled and information concerning the ground conditions and construction tolerances shall be monitored during execution.

The consolidation process shall be monitored by appropriate settlement observations.

NOTE: The final primary consolidation settlement may be estimated with good accuracy from the time-related settlement observations (see Appendix A).

The consolidation process shall also be verified by appropriate methods of pore pressure observations, especially in the case of stability problems or when the observational method of design is used.

Where relevant, lateral time-related movements along the outer boundaries of the loaded area shall be monitored. Appropriate methods shall be used to evaluate these movements (e.g. by inclinometers).

The frequency of settlement and pore pressure observations shall be adjusted to make a realistic interpretation of the consolidation process possible.

Monitoring instruments shall be installed early enough to have stable reference values before the start of the loading process.

Where relevant, the strength increase of the ground may be confirmed by means of laboratory tests on sampled specimens and/or in situ tests.

5.3 RECORDS

5.3.1 Records during construction

Records shall be made of relevant aspects of drain installation, tests and observations as described in Section 4, Clause 5.1 and Clause 5.2. The records shall be made available daily to the client or client representative.

5.3.2 Records during the preload period

Records, observations and monitoring results of any tests shall be made available to the client or client representative.

5.3.3 Records at the completion of the work

Records shall be made of the as-built works, including the following:

(a) Supervision and monitoring records as per Clauses 5.3.1 and 5.3.2.

(b) Information detailing the completed drain installation, including test results, and any changes from the design drawings and specifications.

(c) Details of materials and products used.

(d) Details of relevant geotechnical soil conditions.

(e) Details of instrumentation and monitoring results.

SECTION 6 SPECIAL REQUIREMENTS

6.1 GENERAL

Only those aspects of site safety and protection of the environment that are specific to vertical drainage are considered in this Section.

All relevant national Standards, specifications and statutory requirements regarding safety and environment during execution of the work shall be respected.

The drain installation shall not damage existing underground utilities.

6.2 SAFETY

The installation equipment shall comply with Federal and State safety rules regarding construction and stability. Documents regarding operation, maintenance and safety shall be present in the installation equipment. Workers shall be trained according to Federal and State safety regulations regarding cranes and tall plant.

If the drain installation machine is 50 t or lighter, it shall be equipped with a certified roll over protection structure (ROPS) in accordance with ISO 12117-2 to protect the operator against the machine overturning.

The working platform shall have sufficient bearing capacity to carry the load of the installation machine.

To confirm that the working platform has sufficient bearing capacity to carry the load of the installation machine, the total area shall be tested with a rubber-tyred fully loaded wheel loader or laden dump truck for determining weak spots in the working platform.

During the drain installation works, in case two or more installation machines are working on the same working platform, they shall be separated horizontally by a distance larger than the total height of the machines.

In the case of drain installation close to existing powerlines or underground utilities, attention shall be paid to relevant safety regulations.

High winds could jeopardize the stability of the installation machine. In such cases, reference shall be made to the contractor’s plant risk assessment.

6.3 ENVIRONMENTAL PROTECTION

Construction shall identify and take into account environmental restrictions such as noise, vibrations, water pollution and impact on adjacent structures, as well as the potential for induced currents in existing services.

If contaminated groundwater is squeezed out of the soil through the drains during the consolidation process, it shall be treated. Groundwater that is squeezed out of the soil shall be tested for contamination and possible acid sulfates and, if required, treated prior to release from the site.

At certain locations, the installation of drains may create a connection between aquifers, which can be detrimental to the environment. This shall be assessed and the design modified if necessary.

6.4 IMPACT ON ADJACENT STRUCTURES

Where sensitive structures or unstable slopes are present in the vicinity of the site or the possible zone of influence of the works, their condition shall be carefully observed and documented prior to and during the works. Special preloading requirements may need to be established and adopted at such locations. Vacuum consolidation or other ground improvement methods may also be considered.

APPENDIX A

PRACTICAL ASPECTS OF VERTICAL DRAINAGE

(Informative)

A1 INTRODUCTION

In cases where external loading of low-permeability soils causes a stress increase exceeding the preconsolidation pressure of the soil, excess pore water pressure will be induced, followed by a consolidation process in which pore water is squeezed out of the soil. The volume decrease of the soil caused thereby is accompanied by a gradual increase in effective stress and a corresponding decrease in excess pore water pressure. The consolidation process will continue until the excess pore water pressure has completely dissipated and the load is carried by effective stresses, a process whose duration depends on the consolidation characteristics of the soil and the drainage paths (the longer the drainage paths, the longer the consolidation process). The aim of vertical drain installation is to shorten the drainage paths and the time required for the excess pore water pressure, induced by the loading operation, to dissipate. The time of excess pore water pressure dissipation (the consolidation time) will be shorter the closer the drains are installed.

A2 FIELDS OF APPLICATION

As outlined in Paragraph A1, the installation of prefabricated vertical drains is carried out as a means of speeding up long-term consolidation settlements generated from loading. Another objective is to improve stability conditions by an overall increase in shear strength. In seismic regions, vertical drainage may also be used for the purpose of mitigating liquefaction phenomena.

Examples of areas where this technique has generally been applied are:

(a) Embankments for roads and railroads (Refs 6 to 15).

(b) Construction and reinforcements of levees.

(c) Embankments for construction sites of housing estates, industrial estates, terminals (preloading for landfills).

(d) Marine constructions and near-shore applications (Refs 16, 17).

(e) Land reclamation, ports and airports (Refs 5, 18 to 22).

Vertical drains have also been used as a means of electro-osmotic dewatering. In this case, electrodes are inserted into the prefabricated flat drains and connected to a voltage gradient Refs 2, 23). The rate of consolidation thus achieved will be influenced by the voltage gradient and the electro-osmotic permeability coefficient.

A growing area of application is in the environmental field, remediation of contaminated ground. Contaminated water squeezed out through the drains may have to be treated before disposal.

The typical design life of prefabricated vertical drains is normally limited to a maximum of about 5 years with the exception of drains used for liquefaction mitigation where the lifetime needs to be significantly longer.

A3 EXECUTION OF VERTICAL DRAINAGE

The functional requirements of the project form the basis for the geotechnical design of vertical drainage. The execution of a vertical drainage system is shown in Figure A1. It includes the creation of a working platform, the placement of a drainage blanket, positioning of the drain pattern and installation of the drains, followed by the loading operation and monitoring.

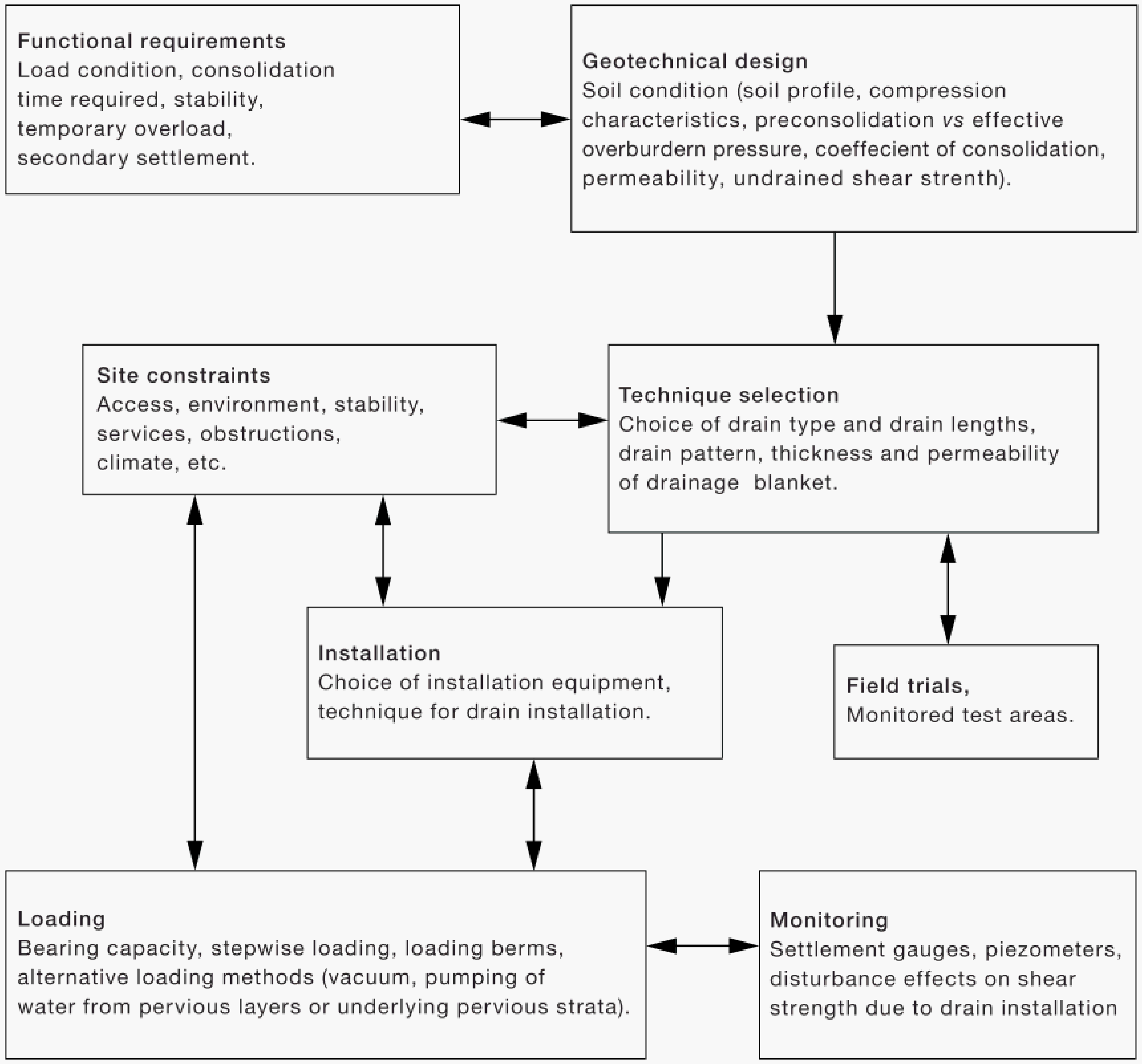
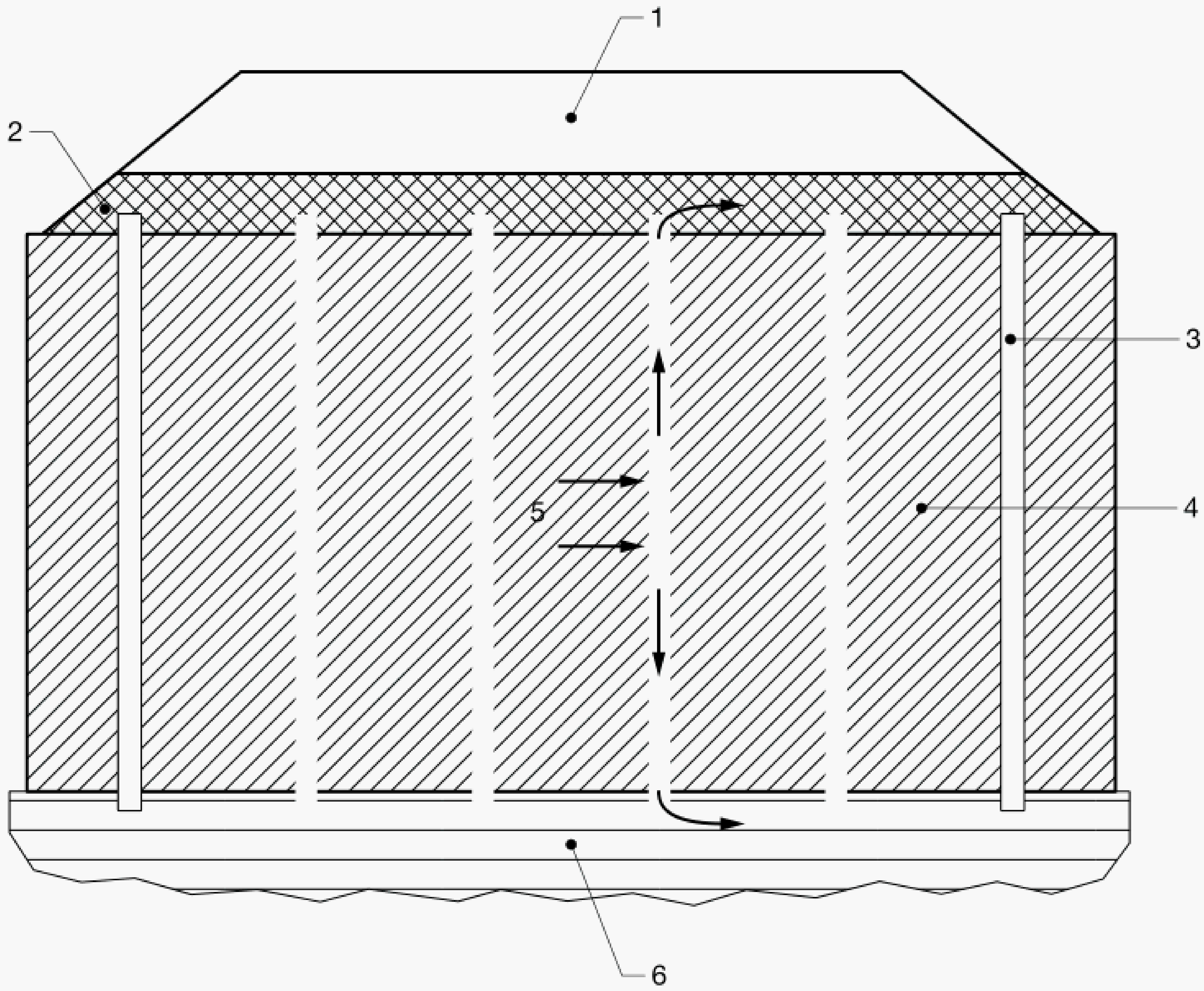


FIGURE A1 CHART OF EXECUTION OF VERTICAL DRAINAGE SYSTEM (EN 15237)

Prefabricated drain types have gradually replaced sand drains, which previously were used frequently. The installation of vertical drains may detrimentally affect the original properties of the soil (e.g. decrease the shear strength and coefficient of consolidation) (Refs 24, 25). A possible decrease in shear strength has to be taken into account in cases where stability under loading conditions may be threatened. Vertical drainage and preloading are illustrated in Figure A2. Due to the excess pore water pressure created by loading, pore water is squeezed out of the soil in the horizontal direction towards the drains and thereafter in the vertical direction through the drains. Generally, a smaller amount of water is also squeezed out of the soil in the vertical direction between the drains (contributory effect of one-dimensional consolidation).

Depending upon the installation method and procedure used, the installation of vertical drains may affect the original properties of the soil (e.g. decrease the shear strength and coefficient of consolidation). This should be considered in the design.



LEGEND:
1 surcharge load
2 drainage blanket
3 vertical drains
4 clay layer
5 pore water flow
6 stiffer soil layer

FIGURE A2 SKETCH SHOWING FULLY PENETRATING DRAINS (DRAINS IN CONTACT WITH DRAINAGE LAYERS AT TOP AND BOTTOM), DRAINAGE BLANKET AND SURCHARGE LOAD (EN 15237)

A4 DRAIN TYPES

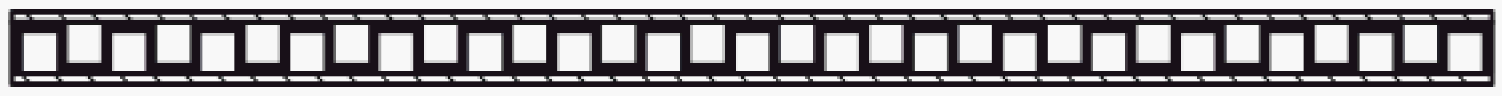
A4.1 Flat drains

A4.1.1 *General*

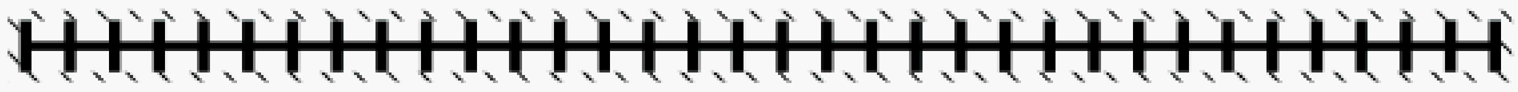
Prefabricated flat drains consist typically of a central core surrounded by a filter sleeve (see Figure A3). The width of the flat drains is typically 100 mm.

A4.1.2 *Types*

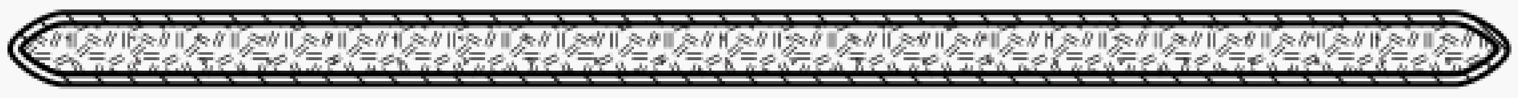
Examples of flat drains are shown in Figure A3.



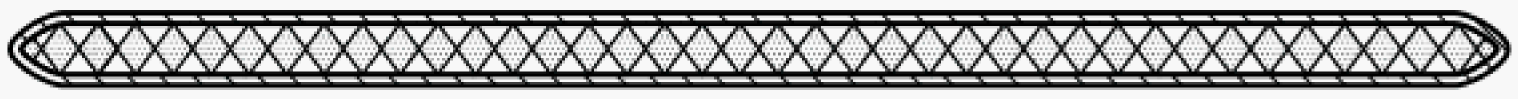
(a) Channel-shaped core with glued filter



(b) Channel-shaped core with wrapped filter



(c) Geo-mat with edge-sealed filter



(d) Cusp-shaped core with wrapped filter

FIGURE A3 EXAMPLES OF FLAT DRAINS (EN 15237)

A4.1.3 *Methods of installation*

Flat drains are installed inside a hollow mandrel with rectangular, rhomboid or circular cross-section. The size of the mandrel is normally adapted to leave a free inside space for the flat drain during installation. The bending rigidity of the mandrel needs to be high enough to ensure verticality of the drain installed.

An anchor plate, which is fixed to the drain toe before installation, prevents the drain from being dragged up when the mandrel is withdrawn (see Figure A4). During installation, the soil should be prevented from intruding between the inside surface of the mandrel and the drain. Otherwise, the drain will be subjected to high tensile forces upon withdrawal. The shape of the mandrel and the anchor needs to be fitted to prevent soil intrusion into the mandrel.

The penetration of the mandrel is either performed by means of a static load or by dynamic action, using a vibratory or impact hammer (Ref. 26). Static installation is preferable in soils sensitive to disturbance.

After withdrawal of the mandrel, the drains should be cut in a way to ascertain good contact with the drainage blanket, preferably about 0.25 m above the working platform.

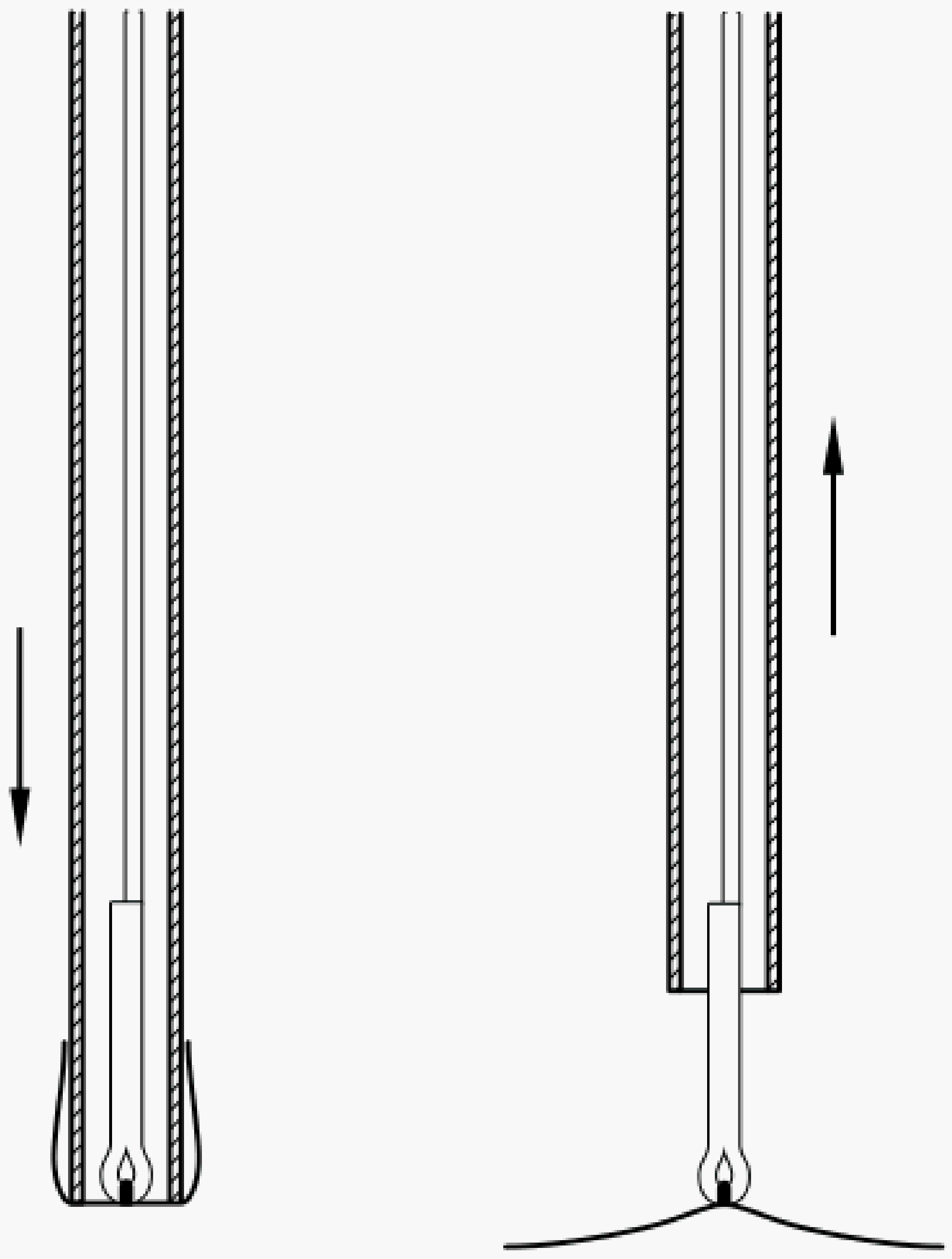


FIGURE A4 EXAMPLE OF FLAT DRAIN ANCHOR (EN 15237)

A4.1.4 *Precautions for the drain installation*

The tensile strength of the flat drain needs to be high enough to prevent breakage of the drains during and after installation. The required tensile strength depends upon the type of execution equipment, installation technique, soil conditions and depth of the drain.

Static installation is preferable to dynamic installation in soils sensitive to disturbance.

The drain installation produces a zone of smear around the mandrel in which the permeability in the horizontal direction for certain types of soil, particularly fine-grained soils with coarser layers, may be considerably reduced.

In some cases the undrained shear strength of the soil may be high enough to resist a collapse of the hole created by the mandrel and thus leave an open space between the drain and the soil when the mandrel is withdrawn. This makes it difficult to estimate the effect of smear as well as the nominal drain diameter to be used in the design.

A4.1.5 *Factors influencing the flat drain efficiency*

A4.1.5.1 *Discharge capacity*

It is important that the discharge capacity of the drains installed in the soil (the amount of water flow per time unit in the vertical direction through the drain under a hydraulic gradient equal to one) be sufficient to achieve the required degree of consolidation in accordance with the design.

The required discharge capacity (see Appendix B) depends on the depth of drain installation, the drain spacing (higher with increasing depth of installation and decreasing drain spacing) and the consolidation characteristics of the soil (higher with increasing permeability and compressibility).

The actual discharge capacity of the drains installed in the soil is influenced by the flat drain properties, the drain installation method (including the effects of smear zone, the hole created by the mandrel and the presence of air in the drain) and by the interaction between the soil and the drain (lateral earth pressure against the drain, possible clogging of the filter and/or the core and effect of buckling).

In highly compressible soil, the relative compression, taking place during the consolidation process, may cause buckling or kinking of the drains, which may seriously reduce their discharge capacity (see Figure A5). Buckling usually takes place in the upper part of the soil; however, the extreme buckling conditions shown in Figure A5 can be expected only in very deformable soils with vertical strains of the order of 50%. This is not the case in ordinary soil and loading conditions, where the vertical strains are typically 10% to 15% and buckling phenomena have no influence on the discharge capacity.

FIGURE A5 BUCKLING AND KINKING OF DRAIN DUE TO VERY LARGE RELATIVE COMPRESSION (EN 15237)

A4.1.6 *Drainage blanket*

For the efficiency of the vertical drainage system, an appropriate drainage blanket (a layer of granular material of appropriate thickness and/or an appropriate drainage system of geotextile or geotextile-related products) needs to be installed to eliminate the risk of a build-up of backpressure in the drains by the water squeezed out through the drains (see Paragraph A4.5). Backpressure in the drains reduces the hydraulic gradient created between the soil and the drains and prolongs the consolidation process.

The drainage blanket should be protected from frost effects when used in cold regions.

A4.1.7 *Determination of flat drain discharge capacity*

The discharge capacity of flat drains depends on the drain structure and its constituents. It may be determined at the end of the fabrication process by means of tests that account for the main factors influencing the discharge capacity; that is lateral pressure against the drain, which causes intrusion of the filter into the channels of the core, intrusion of fine soil particles into the channels through the filter, possible clogging of the channels, effects of buckling on the channel area and effect of temperature. These tests are normally included in a quality control procedure and they do not need to be remade for each flat drain installation job. The discharge capacity characteristics should be used by the designer and referred to in the drain installation statement (see Section 4).

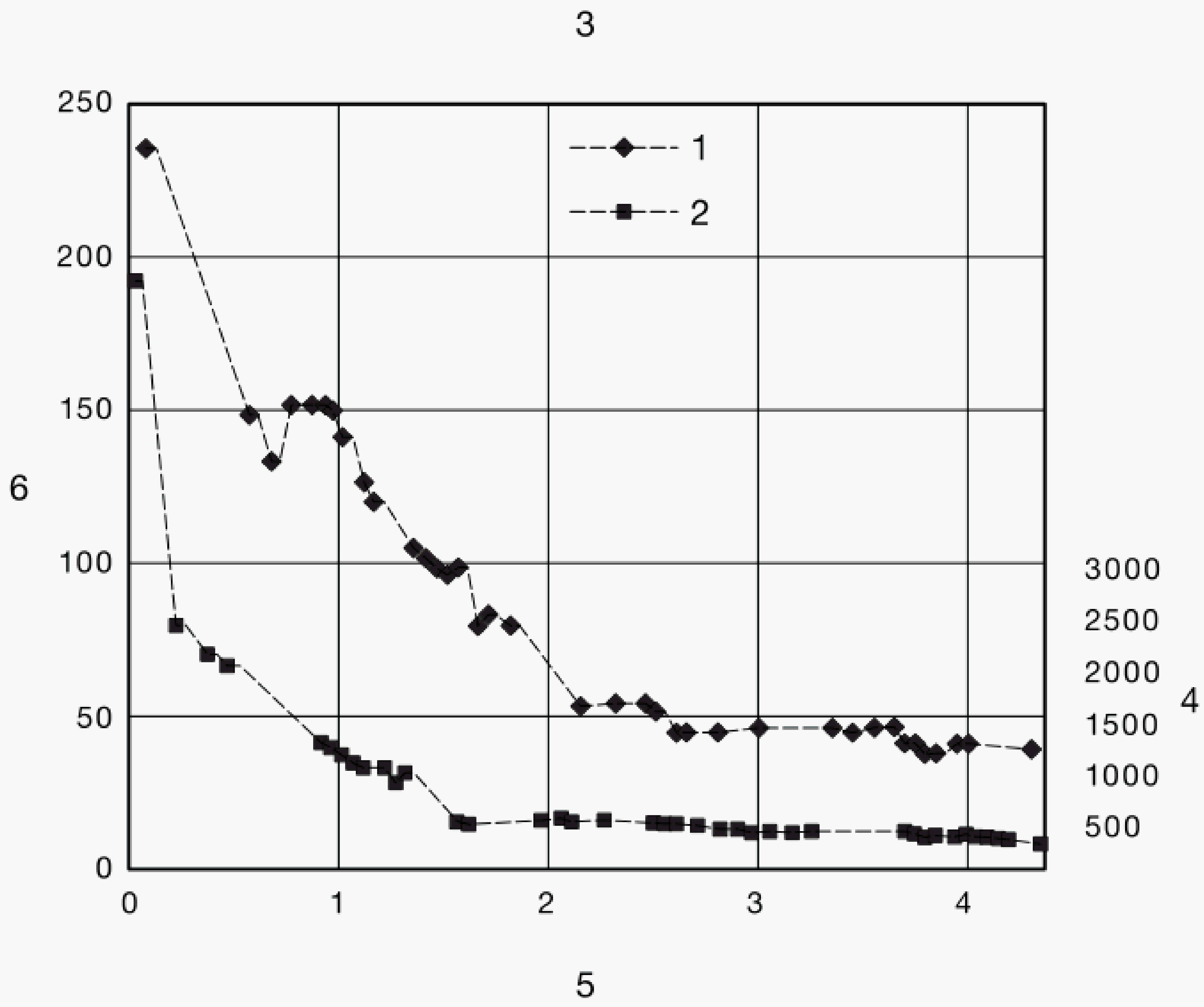
A4.1.7.1 *Discharge capacity of straight flat drains*

The discharge capacity may be derived from the flow capacity measured according to EN ISO 12958 or ASTM D4617.

The duration of the test should also be taken into account and a creep factor (f_{cr}) should be applied to the value of in-plane flow capacity (q_p).

The duration of the discharge capacity test will influence the in-plane water flow capacity due to creep of the filter, which causes an intrusion of the filter into the channel system, thereby reducing the discharge capacity (see Figure A6). The creep factor (f_{cr}) is used to estimate the value of the stabilized discharge capacity from the result of a test of shorter duration (see Table A1), which depends on the testing apparatus and should be determined or checked for each testing device.

The variations of discharge capacity of a flat drain with time, as measured in the different testing devices, are presented in Figure A6.



LEGEND:
1 apparatus 1 (ASTM)
2 apparatus 2 (Delft)
3 discharge capacity straight at 30˚C, 500 kPa
4 discharge capacity, m³/year
5 time, weeks
6 discharge capacity, cm³/s

FIGURE A6 CREEP EFFECT ON DISCHARAGE CAPACITY OBSERVED IN THE DURATION OF A DISCHARGE CAPACITY TEST (Ref. 27)

TABLE A1

CREEP FACTORS (VALUES IF HISTORICAL DATA ARE MISSING)

Testing period	Creep factor (f_{cr})	
Days	Apparatus 1	Apparatus 2
2	10	5
7	8	3
30	3	1

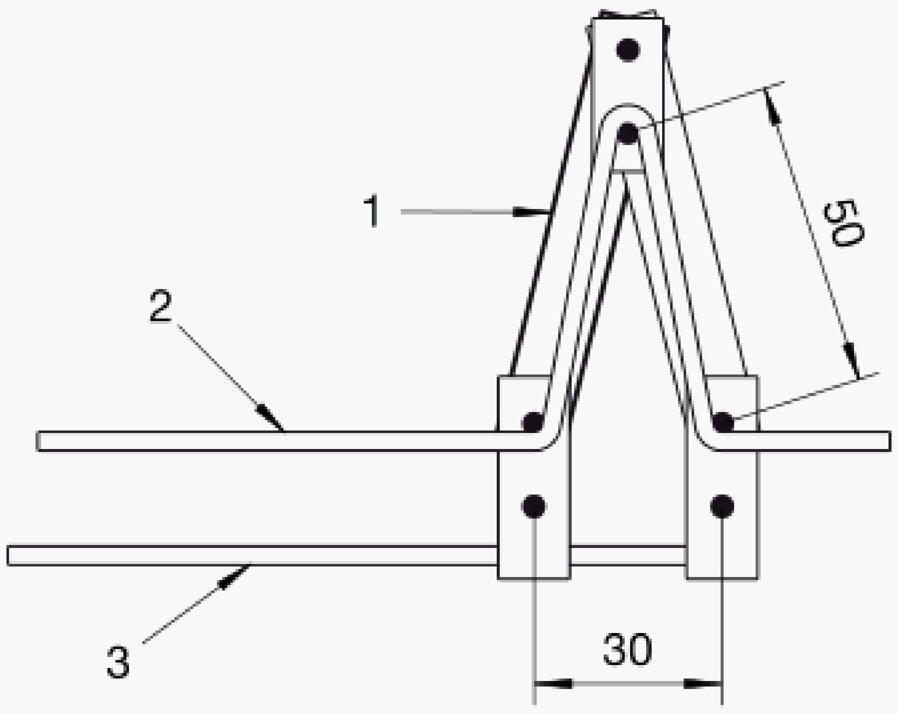
Generally a creep factor (f_{cr}) of 3 is applied to the discharge capacity on ASTM discharge capacity tests.

The discharge capacity tests should be performed with a hydraulic gradient of 0.1 under, respectively, the static pressures 20 kPa, 100 kPa and 200 kPa, possibly also under higher static pressure with regard to the specific design conditions.

A4.1.7.2 *Discharge capacity of buckled flat drain*

The influence of buckling on the discharge capacity of a given flat drain should be considered in the design when the estimated vertical strain of the soil around the drain is high (typically more than 20%).

The discharge capacity test on buckled drains should be performed with a hydraulic gradient of 0.1 under, respectively, the static pressures 20 kPa, 60 kPa and 120 kPa, possibly also under higher static pressure with regard to the specific design conditions. This can be done, for example, by means of the apparatus shown in Figure A7 for the type of apparatus required by EN ISO 12958.



LEGEND:
1 rod A
2 drain sample
3 guide rod

FIGURE A7 EXAMPLE OF APPARATUS TO TEST DISCHARGE CAPACITY OF BUCKLED DRAIN (Ref. 28)

A4.2 Prefabricated round drains

A4.2.1 *Type of drains*

A prefabricated drain consists of a tubular core, typically 30 mm to 50 mm in outer diameter and 2 mm to 5 mm in thickness, made of annular-corrugated perforated plastic, resistant to crushing, shocks, rapid tension and ageing, surrounded by a filter sock made of non-woven geotextile.

A4.2.2 *Method of installation*

The prefabricated round drains are installed inside a hollow mandrel with internal dimensions larger than the external diameter of the drain. The mandrel, which is normally pushed into the soil by static loading, needs to have sufficient rigidity. An anchor plate is fixed to the drain tip before installation, which prevents soil from intruding into the mandrel during installation.

Upon withdrawal of the mandrel, the drains are cut in a way to ascertain good contact with the drainage layer, preferably 0.25 m above the working blanket.

A4.2.3 *Factors influencing drain efficiency*

Round drains are deemed to have sufficient discharge capacity for any vertical drain project. The only recognized factor that may limit their efficiency is the existence of a smear zone around the drain, created by the insertion of the mandrel.

A4.2.4 *Other fields of application*

Annular-corrugated perforated round drains that consist of a pipe of high-density polyethylene, surrounded by a non-woven geotextile filter, have been developed in USA for reduction of liquefaction potential in earthquake regions (Ref. 29).

A5 DRAINAGE BLANKET AND WORKING PLATFORM

For the efficiency of the vertical drainage system, an appropriate drainage blanket (a layer of granular material of appropriate thickness and/or a geotextile or geotextile-related products) should be installed. The consolidation settlement causes a depression of the central part of the drainage blanket. Therefore, temporary wells for removing drained water from the drainage blanket may be required, especially in cases where the width of the drainage blanket is large. At sites of poor trafficability, a working platform may be needed and the option of using the drainage layer, probably thicker, as the working platform may be economical. For example, in the case in most reclamation projects, the working platform usually consists of sand and so the combined working platform and drainage layer thickness may remain adequate for drainage even under differential settlement of the site. Protection of the drainage blanket against frost effects should be considered where relevant.

The permeability of the drainage blanket shall be high enough not to cause backpressure in the drains. Performance-rated laboratory tests provide confidence on the suitability of materials.

The execution of a vertical drainage project requires the presence of a working platform with an upper surface suitable to facilitate the vertical installation of the drains. The working platform has to be capable of carrying the installation equipment. The presence of pockets and lenses of soft soil in the working platform can significantly reduce the local bearing capacity and result in overturning of the installation machine. The placement of a geotextile separation layer underneath the working platform may be a way of avoiding the risk of heterogeneities in the working platform.

A6 LOADING

The loading operation usually consists of placing a surface load on top of the drainage blanket. This is a critical phase of vertical drainage projects. Loading needs to be carried out in such a way that the stability of the ground is not endangered. Therefore, the unit weight of the fill used for loading has to be defined and controlled. The undrained shear strength of the soil may be detrimentally affected not only by the drain installation itself but also by the loading operation if carried out with heavy equipment. In most cases, it is important that the filling operation be monitored by settlement and pore pressure observations.

If the shear strength of the soil is too low to permit placement of the fill to full height, loading berms are required. Alternatively, loading has to be carried out in a staged manner, followed by investigation of the gain in shear strength and dissipation of excess pore water pressure during the consolidation process required to permit the placement of the next load-stage, and so on. In the case of step-wise loading, the specified thickness of each embankment layer needs to be checked in order to avoid excess loading and consequential failure (Ref. 30).

Usually, on large scale reclamation projects, surcharge consists of hydraulically placed sand by dredger. The wet placement can raise the groundwater level over a period of many months and the effects of delay in vertical drainage discharges has to be taken into account by designers.

Groundwater lowering in permeable strata in connection with the drains may also be used as an alternative to, or in combination with, external loading.

At sites of drain installation where the stability conditions are unsatisfactory, the surface load may be replaced or augmented by the vacuum method (see Figure A8). In this case, the drainage blanket is overlain by an airtight cover and sealed hermetically along its outer borders. The drainage blanket is connected to a vacuum pump, which produces under-pressure in the drains in relation to the pore water pressure in the soil, which results in consolidation (Refs 5, 19, 31 and 36). In this case, the under-pressure achieved by the vacuum method is maximum 70 kPa to 80 kPa.

The general characteristics of vacuum preloading compared to conventional preloading are as follows (Refs 37, 38):

(a) The effective stress related to suction pressure increases isotropically, whereby the corresponding lateral movement is compressive. Consequently, the risk of shear failure can be minimized even at a higher rate of embankment construction, although any 'inward' movement towards the embankment toe should be carefully monitored to avoid excessively high tensile stresses.

(b) The vacuum head can propagate to a greater depth of subsoil via the prefabricated vertical drain system and the suction can propagate beyond the tips of the drain and the boundaries of the prefabricated vertical drain zone.

(c) Assuming there are no air leaks and depending on the efficiency of the vacuum system used in the field, the volume of surcharge fill may be decreased to achieve the same degree of consolidation.

(d) Since the height of the surcharge fill can be reduced, the maximum excess pore pressure generated by vacuum preloading is less than the conventional surcharge method.

(e) With the applied vacuum pressure, the inevitable unsaturated condition at the soil-drain interface may be partially compensated for.

(f) With field vacuum consolidation, the confining stress applied to a soil element may consist of two parts—

    (i) vacuum pressure and

    (ii) lateral earth pressure.

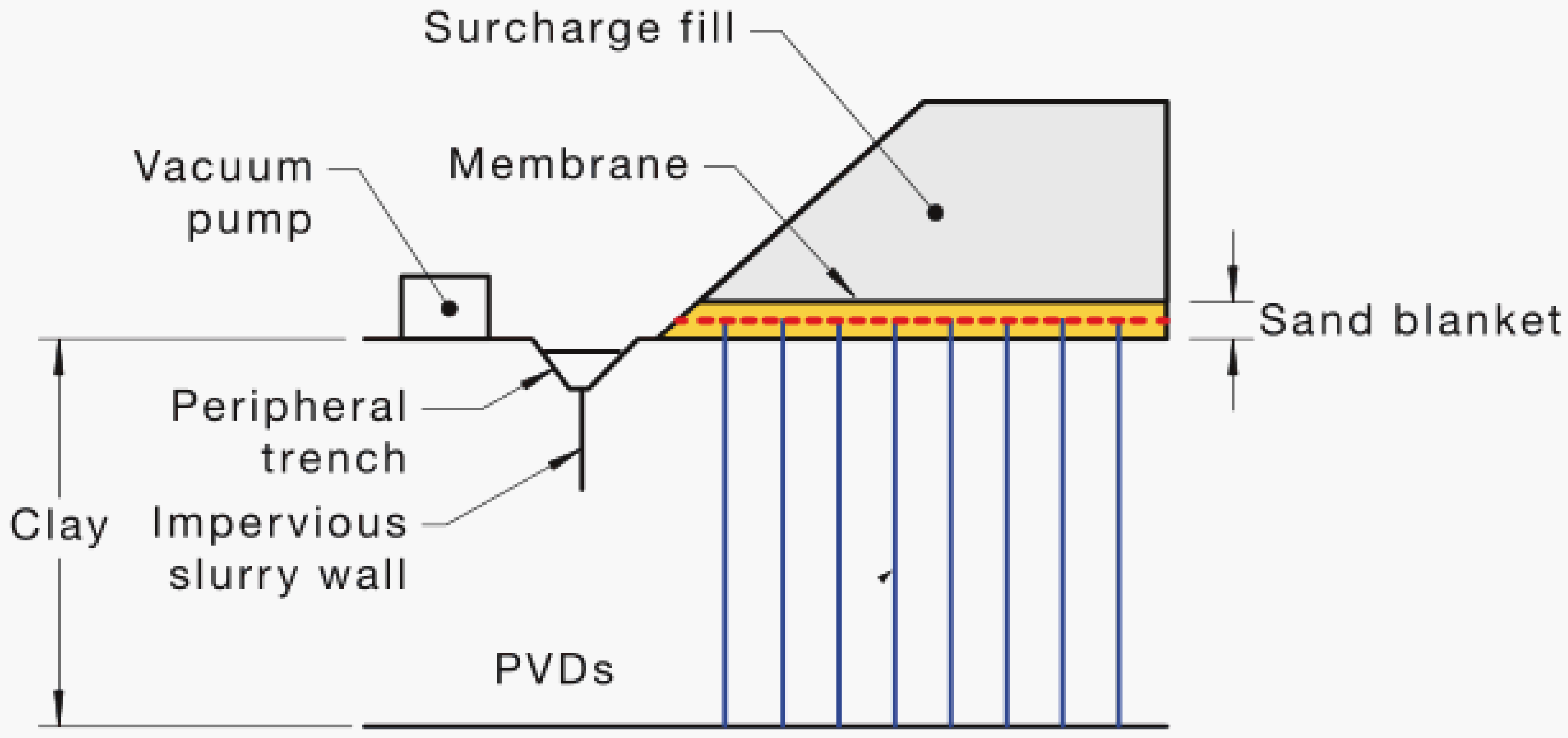
It is essential with vacuum-assisted preloading that a network of horizontal drains be placed after installing the sand blanket, in order to uniformly distribute the surface suction. Horizontal drains can then be connected to the edge of the membrane and linked to the vacuum pump via a collector pipe.

Generally, the periphery of the vacuum area can be sealed using a bentonite slurry trench (see Figure A8).

Where deeper sand lenses are present in the soil profile, cut-off walls would generally be used at the periphery.

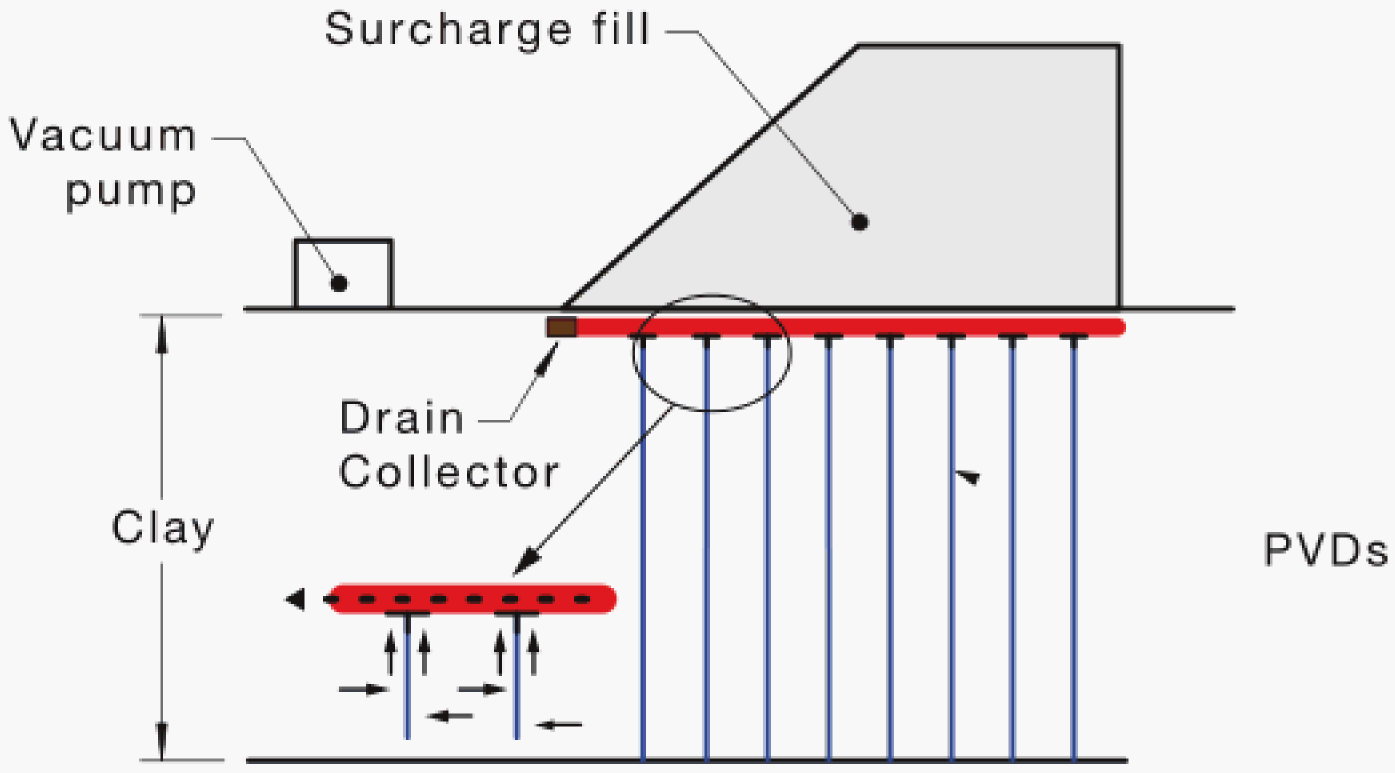
Where a granular layer is present at a given depth following the soft clay deposit, the tip of the vertical drains will need to be located above the granular layer to prevent vacuum loss.

An alternative method is to apply the vacuum directly to the individual prefabricated vertical drain with flexible tubes without using a membrane (Ref. 39). Here, each prefabricated vertical drain is connected directly to the collector drain (see Figure A8) and will act independently. An advantage is that an airtight cover over the whole area is not needed as in the conventional system. In practice, the maximum under-pressure achieved is significantly less, perhaps up to 50 kPa or so.



(a) Membrane system

NOTE: Impervious slurry wall if required.



(b) Membraneless system

FIGURE A8 VACUUM-ASSISTED PRELOADING SYSTEM (Ref. 34)

A7 MONITORING

The effect of vertical drainage may be monitored by both settlement and pore pressure measurements. The measured values are used to check the actual rate of consolidation and the assumptions made in the design. It is important that the monitoring system be installed in due time before the installation of the drains.

The aim of soil improvement by vertical drainage is generally to prevent unacceptable settlement from taking place under service conditions. Therefore, settlement observations are a necessary ingredient in the monitoring system.

The traditional method is to monitor settlements by placing settlement plates on the ground surface prior to any fill placement, where the subsurface compressible clay layer is thick and/or the profile is layered, deep settlement gauges/extensometers may be useful to differentiate the contribution from various soil layers.

Excess pore pressure observations by means of piezometers installed at different depths is doubtless the most appropriate way of checking that the degree of consolidation has reached the set level according to the design. The piezometers should be placed in the centre between the drains where the rate of consolidation is a minimum; however, the interpretation of the results of pore pressure measurements can be quite intricate. The results will depend on the position of the piezometer in relation to the drain (Ref. 33) (which may differ from intended position), the piezometer (the filter tip) will move downwards in the course of consolidation, the results may be affected by pore backpressure from the surroundings, gas evolution may give erroneous results, etc. Moreover, the pore pressure situation after completed consolidation may not revert to its original equilibrium condition. In spite of the problems, pore pressure measurements could be useful in certain circumstances such as when low target percentages of consolidation and/or consolidation over short duration need assessment.

In vacuum consolidation sites, pressure gauges installed under the membrane provide pressure distribution across the area. Piezometers installed within drains at different depths may provide valuable information on the vacuum pressure.

It is preferable to locate the piezometers and settlement plates close to test locations to facilitate back calculations based on monitoring results.

For any project, it is important that an instrumentation plan be set up by the designers soon after the design is completed. The instruments and the locations should be identified to provide critical data required to monitor the performance of the construction and take necessary action if the behaviour is different to the anticipated.

The most used instrument type in construction is the settlement plate or settlement point/marker. Settlement points/markers are used to either monitor locations outside the footprint of earthworks (e.g. pipe/building foundation) or on the surface of the surcharge/preload. They are less expensive; therefore, smaller spacings may be adopted.

Settlement plate spacing to be adopted depends on the project, site conditions and what the objective is. For example, for a road project, typically a 100 m spacing may be appropriate for settlement plates but closer spacing is warranted where clay thickness varies, especially if paleo channels are identified or suspected. Closer to structures such as a bridge abutment, such spacing should be reduced to the order of 25 m or so to ensure that longitudinal grade changes are adequately captured. In addition, use of settlement points at a 5 m grid interval within 25 m of a bridge abutment would allow the designer to observe the grade changes in both longitudinal and transverse directions.

Where the project involves the reclamation and/or filling of wide areas, a spacing of about 50 m may be adopted in both directions but the spacing should be reduced where clay thickness varies, especially if a paleochannel is identified or suspected.

The frequency of readings of each instrument has to be planned and advised by the geotechnical consultant. Daily monitoring is generally recommended during construction, close to instrument locations. After the construction is completed, the frequency of settlement may be gradually reduced by the geotechnical consultant, depending on the expected duration of preload. The usual practice is to reduce to bi-weekly, then weekly and, if the preload duration is long, fortnightly or monthly.

Stability is generally critical during construction; and therefore, instruments that provide information related to stability are critical. Lateral movement, increase in pore pressure and ratio of vertical and lateral movement may be used by the geotechnical consultant to assess stability.

APPENDIX B

ASPECTS OF DESIGN

(Informative)

B1 GENERAL

This Appendix covers some specific aspects of the design of vertical drainage systems, including the evaluation of soil characteristics and influence of drain characteristics, drain pattern and depth of drain installation. It does not cover the detailed principles or methods of geotechnical design.

B2 DESIGN PROCESS AND PHILOSOPHY

The overall design process and design philosophy is discussed in Section 3. A simplified design procedure and worked-out example is provided in Appendix C.

B3 INVESTIGATIONS FOR VERTICAL DRAINAGE

B3.1 General

The subsoil characteristics are usually determined by means of field investigation methods (e.g. cone penetration tests, field vane tests and pore pressure observations at various depths) in combination with sampling for laboratory analysis (Refs 40, 41). The pore water pressure distribution with depth forms the basis for evaluation of the effective overburden pressure distribution with depth. This information is required to determine whether or not the soil is over-consolidated or normally consolidated. It should be realized that the pore water pressure may vary considerably with time of the year and amount of precipitation. Occasional high pore water pressure, which reduces the magnitude of effective overburden pressure, can give a false impression of over-consolidated soil.

The testing, and soil identification and classification, which is based on the results of the soil investigation, needs to be carried out in compliance with AS 1726 and the penetration resistance of the soil should be investigated to provide information for selecting the capacity of installation machines.

B3.2 Laboratory investigations

The consolidation and settlement parameters are conventionally determined by oedometer tests on undisturbed soil samples, taken by means of high-quality piston samplers. The results of conventional oedometer tests yield values of the compression modulus, the preconsolidation pressure and the coefficient of consolidation in vertical pore water flow. For determination of the coefficient of consolidation in horizontal pore water flow by oedometer tests, allowance for radial drainage needs to be made; this can be done by using the Rowe cell type tests.

Laboratory testing also includes determination of the undrained shear strength and sensitivity of the soil as well as unit weight, water content and index testing.

Large-scale consolidation testing may be required to obtain the extent of smear zone and the disturbed soil permeability due to the drain installation (Ref. 42).

B3.3 Field investigations

Field investigations normally comprise determination of the undrained shear strength by field vane tests and/or cone penetration tests. The coefficient of consolidation and the permeability in horizontal pore water flow may be evaluated by carrying out dissipation tests using cone penetration equipment with a pore pressure device (CPTU/piezocone) (Refs 43 to 47).

Possible contamination of the pore water may be investigated by sampling of pore water at various depths (Ref. 29).

An assessment of acid sulfate prior to construction, by sampling soil and water, is also important.

B4 ASPECTS OF DESIGN

B4.1 Settlement

B4.1.1 *Total settlement*

The question of whether the soil is normally consolidated or over-consolidated is of great importance for the correctness of the settlement analysis and for whether the use of vertical drainage is adequate or not. A correct determination of the preconsolidation pressure is of paramount importance. The use of prefabricated vertical drains in a case where the effective stresses induced by the loading operation are below the preconsolidation pressure of the soil is counter-productive since the installation of the drains may cause disturbance effects that result in an increase in settlement. Thus, vertical drainage should only be utilized in cases where the preconsolidation pressure will be exceeded by the stresses induced by the loading operation.

The soil deformations caused by external loading include both vertical and horizontal displacements, whose relative magnitudes depend on the loading condition, the shear strength of the soil and the ratio of the width of loading to the depth of the soil layer. Especially if test areas are used as a basis for design, the widths of which are small in comparison with the depth of the soil layer, horizontal displacements may contribute considerably to the vertical settlement observed. In such cases, vertical inclinometers, placed along the borders of the test area, provide information about the influence on the vertical settlement of horizontal deformations.

In the analysis of the total settlement obtained after completed consolidation, the influence on soil deformation properties of possible disturbance effects caused by drain installation should be considered. The disturbance effects depend very much on the method of drain installation, the size and shape of the mandrel and the structural features and undrained shear strength of the soil. To ensure the accuracy of the settlement analysis it is important that the average unit weight of any fill material used for loading given in the specification. It is also necessary to take into account the load reduction due to buoyancy effects if part of a surcharge becomes submerged during the consolidation process.

The total primary consolidation settlement can be estimated from the settlement gradually developed during the consolidation process (Ref. 48). For example, according to Asaoka (Refs 49, 50) the relation established between the settlements observed at equal time intervals (Δt) can be used to assess the final primary consolidation settlement.

The settlement achieved by the use of the vacuum method (see Appendix A) is governed by the effectiveness of the sealing system. Normally, a maximum of 70% to 80% vacuum can be achieved, resulting in an effective stress increase of 70 kPa–80 kPa (Refs 19, 51). In the case of vacuum membrane type system, if the water table is above the membrane level, the resulting effective vertical stress will also include the overburden pressure of the water. Temporary overloading can reduce secondary creep settlement following upon the primary consolidation period. The required temporary overloading depends on the deformation characteristics of the soil and on the secondary consolidation settlement requirements.

B4.1.2 *Rate of consolidation settlement with vertical drainage*

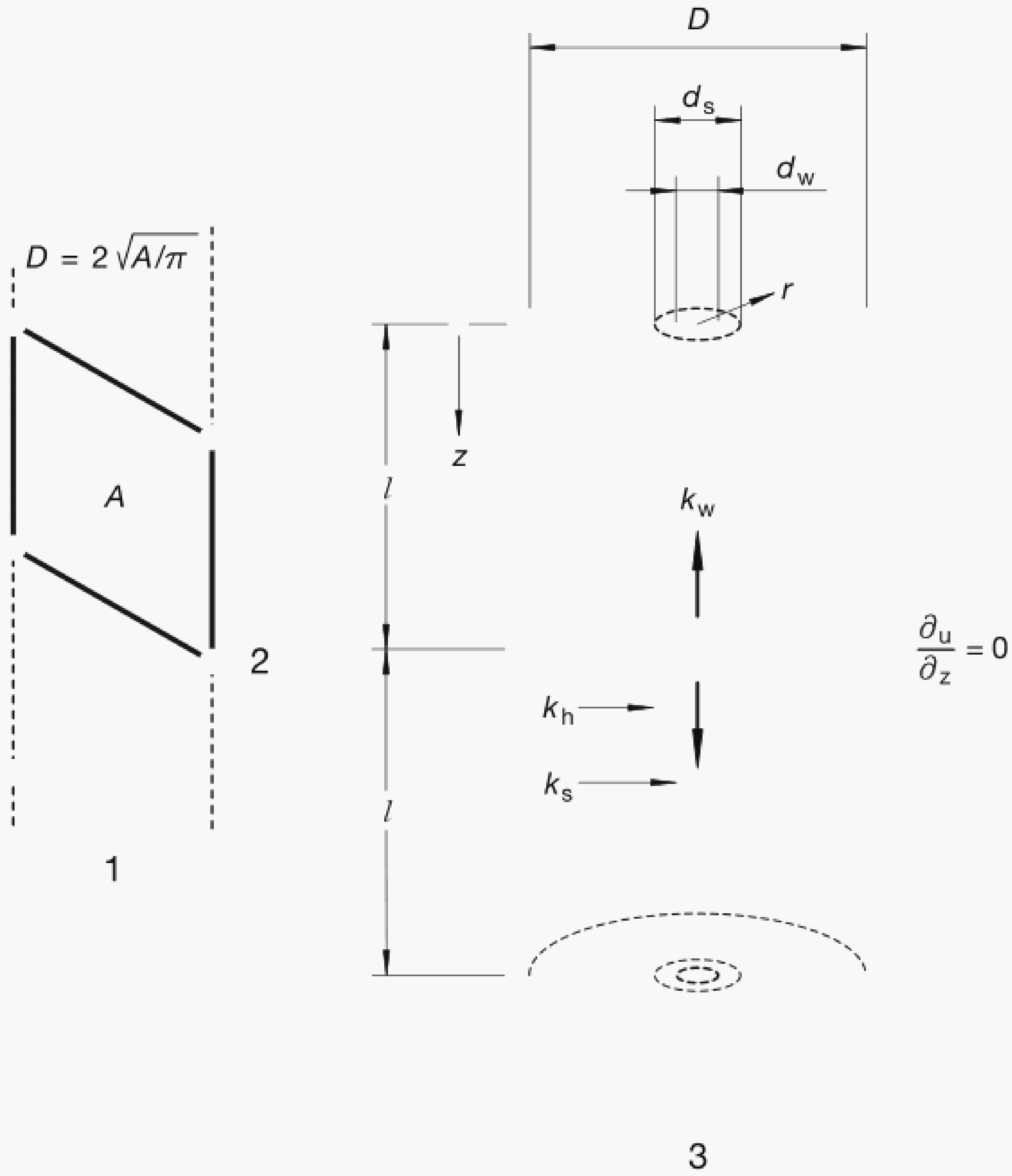
B4.1.2.1 *Design assumptions*

For the analysis of the rate of consolidation settlement, the drainage characteristics have to be identified [diameter (D) of hypothetical soil cylinder dewatered by each drain, drain diameter (d_w), diameter of zone of smear (d_s), discharge capacity (q_w)] as well as the soil consolidation parameters [coefficient of consolidation (c_h), permeability in horizontal pore water flow in undisturbed soil (k_h) and in the zone of smear (k_s)] (see Figure B1).

Vertical drains are commonly installed in square or triangular patterns (see Figure B2). As illustrated in Figure B3, the influence zone diameter (D) is a controlled variable, as it is a function of the drain spacing (S) as given by the following:

$D = 1.13S$ for drains installed in a square pattern, and

$D = 1.05S$ for drains installed in a triangular pattern



LEGEND:
1 plan
2 drain
3 perspective

FIGURE B1 SOIL CYLINDER DEWATERED BY A DRAIN (EN 15237)

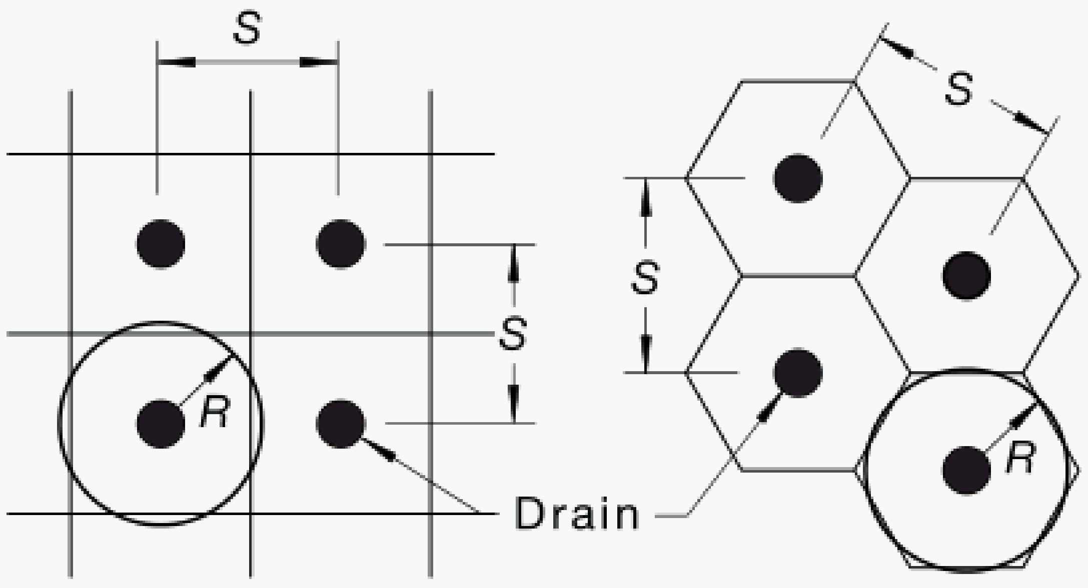


FIGURE B2 PLAN OF DRAIN PATTERN AND ZONE OF INFLUENCE OF EACH DRAIN (Ref. 34)

As shown in Figure B3, the drain diameter (d_w) for a flat drain can be assumed equal to that of a round drain with the same circumference as the flat drain, i.e. $d_w = 2(a + b)/\pi$, where a is the width and b is the thickness of the flat drain (Ref. 52). An independent numerical study (Ref. 53) suggested that d_w could be simplified to $d_w = (a + b)/2$.

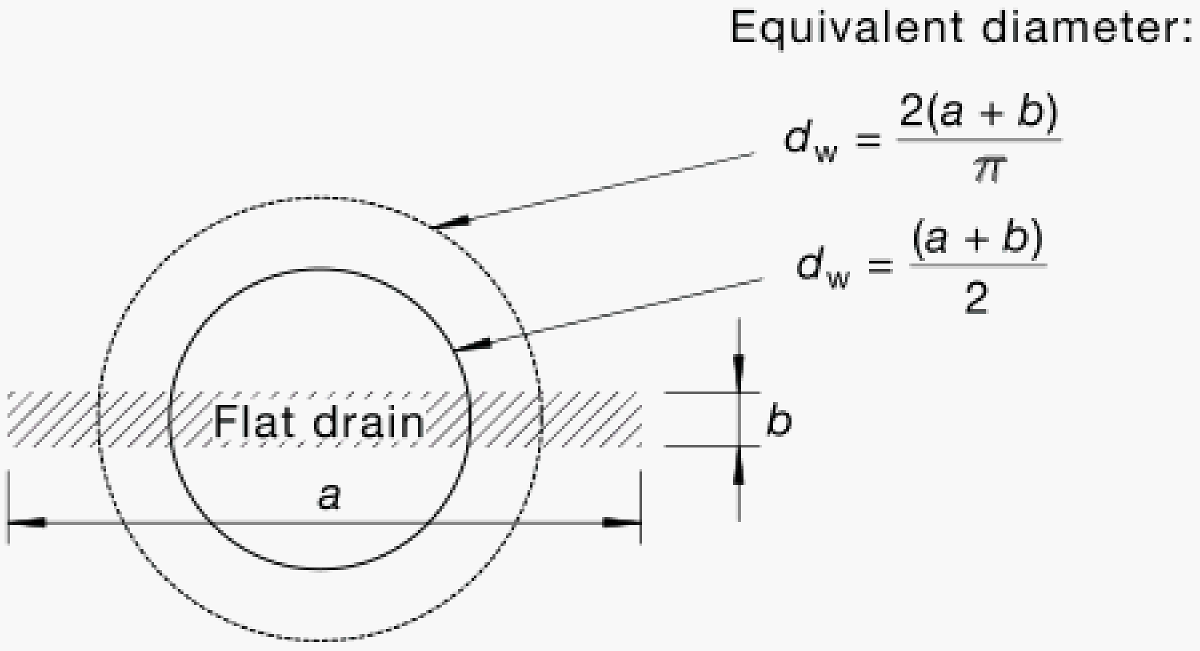


FIGURE B3 EQUIVALENT DIAMETER OF BAND-SHAPED VERTICAL DRAINS (Ref. 34)

The consolidation parameters of the soil are usually based on the results of oedometer tests where excess pore water dissipation takes place in the vertical direction. This differs from the real case with vertical drains where excess pore water dissipation mainly takes place in the horizontal direction. The difference between the oedometer case and reality becomes important where seams or layers exist with higher permeability than the main body of the soil. For the determination of the coefficient of consolidation in horizontal pore water flow, oedometer tests provided with radial drainage, or CPTU (piezocone) tests as described in Paragraph B3.3, may be used.

In some site conditions, the drain installation procedure may increase the soil compressibility and/or decrease the coefficient of consolidation and the permeability of the soil. It may also create excess pore water pressure in the soil. Such perturbations of the initial soil conditions should be considered in the design. When relevant, it is important that monitoring equipment be installed in due time before the drains are installed so that the disturbance effects can be registered and duly considered (Ref. 54).

The insertion of the mandrel into the soil during drain installation also creates a zone of smear where horizontal layers are distorted in the vertical direction, followed by a reduction in horizontal soil permeability. The width and the characteristics of the zone of smear are a function of the installation method.

Several researchers have proposed that the diameter of the smear zone (d_s) and the cross-sectional area of mandrel can be related. For convenience, many designers adopt a relationship between d_s and d_m where the latter refers to the equivalent diameter of the mandrel (based on equivalent cross-sectional area). Some of the relationships found in literature include:

$$d_s = \frac{(5\text{ to }6)d_m}{2} \text{ (Ref. 55)}$$

where

$$d_s = 2d_m \text{ (Ref. 56)}$$

$$= (3\text{ to }4)\ d_m \text{ (Ref. 42)}$$

Indraratna and Redana (Ref. 42) investigated the smear zone extent in the laboratory using a large diameter triaxial cell and the results summarized in Figure B4 show that the variation of k_h/k_v ratio clearly indicates a drop of the permeability ratio within the smear zone. According to Hansbo (Ref. 56) and Bergado et al. (Ref. 57), in the smear zone, the ratio of the smear zone permeability and the vertical permeability in the undisturbed zone can be found to be close to unity under significant remoulding, which is in agreement with the results of the study by Indraratna and Redana (Ref. 42). In most cases where complete remoulding does not occur, a (k_h/k_v) ratio of 1.2/1.3 is a reasonable estimation.

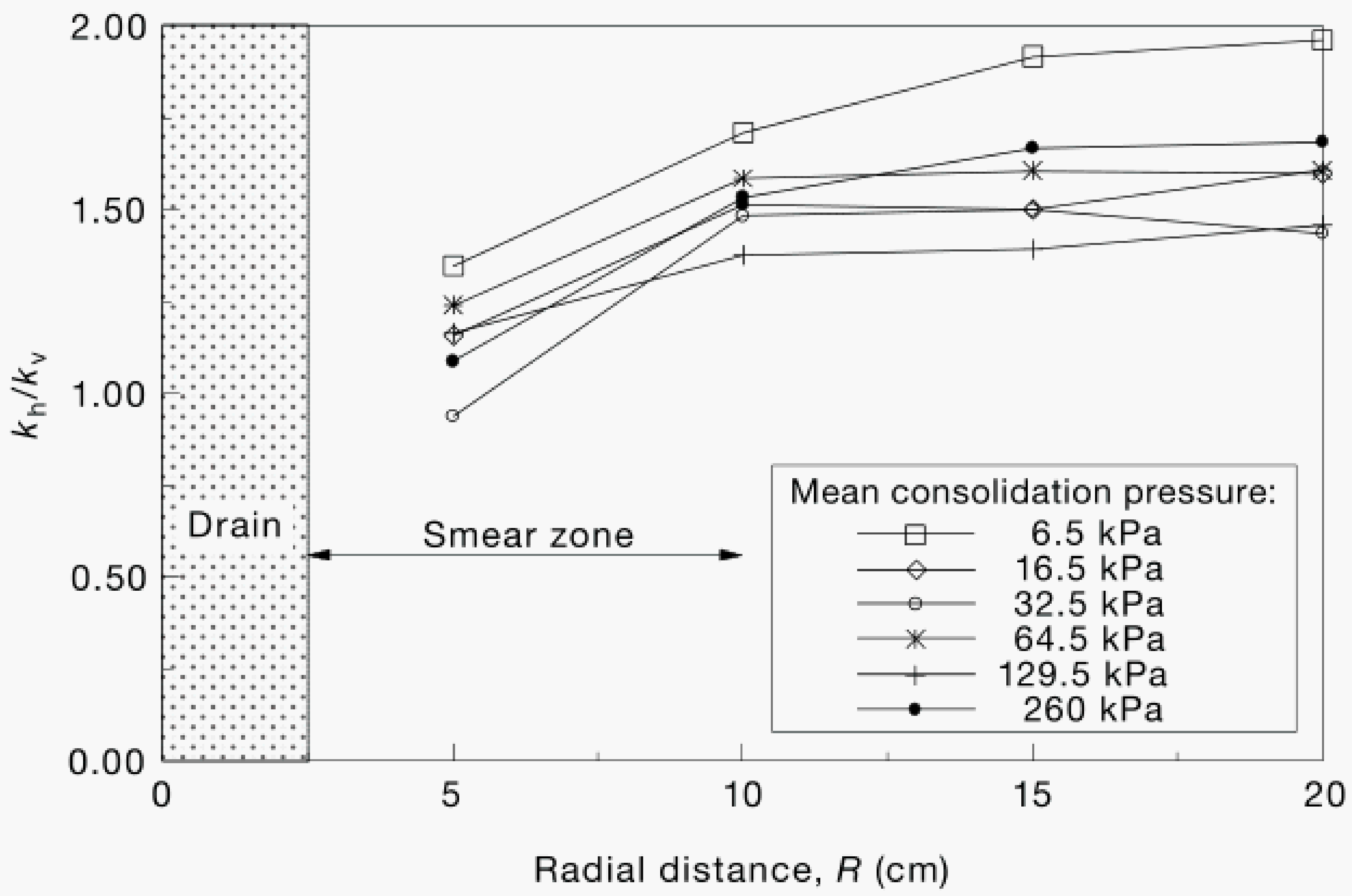


FIGURE B4 RATIO OF k_h/k_v ALONG THE RADIAL DISTANCE FROM THE CENTRAL DRAIN (Ref. 42)

The influence of the smear zone should also be considered with due account taken of the hole created by the mandrel during drain installation. The dimensions of the mandrel are temporarily much larger than those of the drains.

The mandrel used for flat drain installation is not usually filled with water during the installation process. In consequence, a cushion of air may be left between the drain and the surrounding soil after the mandrel is withdrawn. A cushion of air causes a negative effect on the consolidation process, similar to that of smear. This is taken into account in the choice of smear zone parameters based on experience. The installation may also cause vertical cracks in the soil around the mandrel. In cases where the undrained shear strength of the soil is high, the installation may leave an open hole around the drain, which has a favourable effect on the discharge capacity.

Investigations of the characteristics and extent of the zone of smear caused by drain installation have been performed by some (Refs 42, 58 to 63).

Unlike the PVDs used some two to three decades ago, the modern PVDs have better designed drain cores and filters that make their discharge capacities at least 3 to 4 times larger than what is required for deep soft soil stabilization. Detailed large-scale tests conducted have demonstrated that inevitable folding of drains due to vertical and lateral soil movements may have little effect on significantly reducing the initial discharge capacity (Ref. 34).

For most estuarine/marine soft soil deposits in Australia that are generally less than 20 m, the smear effects caused by drain installation present a much greater impact on subsequent consolidation than the well resistance of PVDs. Analytical models developed and calibrated for numerous types of soft clays (Refs 42, 64) imply that well resistance can be neglected in comparison to smear effects, unless the PVD lengths exceed 20 m.

B4.1.2.2 *Method of analysis*

Theoretically, whatever pattern is used, each drain is considered to dewater a hypothetical soil cylinder whose cross-sectional area equals the cross-sectional area enclosed by four neighbouring drains (see Figure B2). The most efficient way of utilizing the capacity of vertical drains for the purpose of speeding up the consolidation process is to install the drains in an equilateral triangular pattern. The consolidation process is mainly governed by pore water flow in the radial direction towards the drain and to a lesser extent by pore water flow in the vertical direction between the drains. Two methods of analysis exist, the so-called 'free strain analysis' and the 'equal strain analysis'. As shown by Barron (Ref. 65), the difference in results regarding average consolidation process obtained between the two methods of analysis is negligible. Therefore, because of its simplicity the equal strain analysis has become routine (Refs 56, 66 to 79).

In the methods of analysis used for determination of the influence of well resistance (limited discharge capacity), the consolidation characteristics of the soil are generally assumed to be constant throughout the soil layer. The influence of layers with different consolidation characteristics has been analyzed by Onoue (Ref. 80).

Another conventional assumption in analysis is the validity of Darcy's law. Experience from a number of field tests (Refs 81 to 83) and from laboratory tests on permeability (Refs 81, 84) has shown that there is a deviation from Darcy's law at small hydraulic gradients. Consolidation equations valid for both Darcian and non-Darcian flow have been developed (Refs 63, 85).

The basic theory of vertical drainage used in routine analysis of most of vertical drainage projects was published by Hansbo (Ref. 66) as an extension of Barron's theory (Ref. 65) for the case of drains with limited discharge capacity (Ref. 86). Accordingly, the rate of consolidation follows the relationship:

$$\bar{U}_h = 1 - \exp\left(-\frac{8T_h}{\mu}\right)$$

where the time factor T_h is defined as:

$$T_h = \frac{c_h t}{D^2}$$

The coefficient of radial drainage consolidation (c_h) is represented by:

$$c_h = \frac{k_h (l+e)}{a_v \gamma_w}$$

where γ_w is unit weight of water and a_v is the coefficient of compressibility of the soil, e is the void ratio, and k_h is the horizontal permeability of the soil in undisturbed zone.

Omitting terms of minor significance, μ parameter may be expressed by:

$$\mu = ln\left(\frac{D}{d_s}\right)+\left(\frac{k_h}{k_s}\right)ln\left(\frac{d_s}{d_w}\right)-0.75+\pi z\,(2l-z)\left(\frac{k_h}{q_w}\right)$$

where

q_w = discharge capacity of the drain

l = length of the drain (assumed closed at bottom end)

z = depth (from open top end of the drain)

B4.1.3 *Safety factors for prefabricated flat drains*

With regard to possible negative effects on the discharge capacity of prefabricated flat drains, consideration has to be taken of the influence of effective lateral soil pressure against the drains, of soil temperature and of long-term biological and chemical activities. In order to guarantee the efficiency of the drains, testing of the discharge capacity of the drains (see Appendix A) should be carried out with due reference to the expected maximum effective lateral pressure against the drains and the temperature condition in the actual project multiplied by certain required safety factors (Ref. 87). How this should be done is exemplified in Appendix A.

B4.1.4 *Estimation of drain spacing using design charts*

While drain spacing could be assessed by a designer using the equations given above, either manually or setting up a simple spreadsheet, some find it convenient to use design charts, at least for preliminary design purposes. A typical set of charts is presented in Appendix C.

B4.2 Other design aspects

B4.2.1 *Filter jacket*

The filter jacket of PVDs have to perform two basic but contrasting requirements, which are—

(a) retaining the soil particles; and

(b) allowing the pore water to pass through.

According to Indraratna and Bamunawita (Ref. 88), the following requirements, if satisfied, should provide the expected performance:

(i) $k_{\text{filter}} > 20\ k_{\text{soil}}$

(ii) $\frac{O_{95}}{D_{85}} \leq 3$ [Bergardo et al (Ref. 89)]

where, O_{95} is the equivalent opening size (EOS) and D_{85} indicates the diameter of clay particles corresponding to 85% passing.

(iii) $\frac{O_{50}}{D_{50}} \leq 24$ (retention ability)

where, O_{50} is the apparent opening size (AOS) at 50% passing and D_{50} indicates the diameter of clay particles corresponding to 50% passing.

(iv) $\frac{O_{95}}{D_{15}} \geq 3$ (prevention of clogging)

where, D_{15} indicates the diameter of clay particles corresponding to 15% passing.

B4.2.2 *Other factors affecting design discharge*

Generally the PVDs are installed in an unsaturated state. Better results may be obtained if saturated conditions can be achieved during installation. For instance, while it may not be practical or cost-effective, the entire roll of PVD could be soaked (saturated) and the mandrel filled with water during installation to negate any unfavourable effects of any air gap at the soil-drain interface when the mandrel is withdrawn (Ref. 90). The presence of air at the interface reduces the apparent permeability of the drain filter, the horizontal permeability of the soil surrounding the drain and the overall drain discharge capacity (Ref. 64, 88). A hydrophilic finish on the filter surface improves the affinity for water.

B4.3 Stability

Stability analysis is very important when soil improvement is undertaken by vertical drain installation and preloading. In the stability analysis of the embankment load placed on the ground surface, no reinforcing effect of the vertical drains is considered; however, estimation and a follow-up of the strength increase produced during consolidation, particularly when stage loading is used, is an important part of the analysis. Under certain circumstances and if space exists, stability berms may be utilized. If such areas are installed with prefabricated vertical drains, even greater stability is afforded to the main surcharge area from strength gain under the berms.

The undrained shear strength, determined in the field (e.g. by field vane tests or cone penetration tests) or by laboratory tests (e.g. fall-cone test, triaxial test or unconfined compression test), should be adjusted with regard to the consistency limits of the soil and to the shearing direction (Ref. 91). If the placement of the external load involves stability problems, the load has to be staged. After each load stage, the gain in shear strength achieved during the consolidation process has to be investigated before the placement of the following load stage, in order that the stability condition is not jeopardized.

A possibility of estimating the strength gain in each load step is to utilize empirical correlations; for example, between liquid limit, undrained shear strength and preconsolidation pressure (Ref. 92) or between plasticity index, undrained shear strength and preconsolidation pressure (Ref. 86). If there is no change in liquid limit or plasticity index during the consolidation process, the relative change in undrained shear strength can be assumed equal to the relative change in preconsolidation pressure. Valuable empirical correlations for estimating the strength gain have also been presented by Mesri (Ref. 93) and Ladd (Ref. 94). Since the preconsolidation pressure increases with effective stress increase in the ground, it depends directly on the degree of consolidation, which characterizes both settlement and excess pore water pressure decrease. Therefore, pore pressure monitoring may form part of the instrumentation for vertical drainage projects, as described in Appendix A.

Stability problems can be avoided by exchanging external loading by the vacuum method or by pumping water from underlying pervious soil (see Appendix A). Normally, 70% to 80% vacuum can be achieved in a membrane type system, which results in an effective stress increase of 70 kN/m^2 to 80 kN/m^2; however, the ratio of vertical to horizontal effective stress increase in the two cases will be different. This will have a different effect on the increase of undrained shear strength caused by consolidation than the increase caused by surface loading.

B4.4 Cyclic loading

In Australia, the effect of cyclic loading and the associated ground improvements are relevant for rail tracks on deep estuarine deposits. While several ground improvement techniques may be applicable, short PVDs driven to the depth of influence, generally 6 m to 8 m, could be very economical. The design procedure that involves obtaining a static pressure equivalent to impact loading and the steps involved is discussed in detail by Indraratna et al (Ref. 6).

APPENDIX C

ESTIMATION OF DRAIN SPACING USING DESIGN CHARTS

(Informative)

C1 DESIGN PROCEDURE

A set of charts is presented below, which was prepared by Rujikiatkamjorn and Indraratna (Ref. 86) to eliminate cumbersome iteration procedures using the equivalent drain diameter as an independent variable to obtain the relevant drain spacing.

The following information should be available prior to using the design charts:

Required parameter	Basis of selection	Comments
Appropriate installation depth (l)	Based on available soil profile and test results	Generally drains are pushed into a competent stratum
Desired consolidation time (t)	Depends on the available time for construction	The time does not include the construction time or the surcharge removal time
Coefficient of horizontal consolidation (c_h)	Usually from CPTU dissipation tests	
Equivalent drain diameter (d_w)	$d_w = 2(a + b)/\pi$ where a is the width and b thickness of the flat drain (Ref. 52) A simplified relationship is $d_w = (a + b)/2$ (Ref. 53)	
Drain pattern and equivalent spacing (D)	$D = 1.13S$ for a square pattern, and $D = 1.05S$ for a triangular pattern	

Once the above information is collected, the design can be progressed. A simplified design procedure and worked example is as follows:

1 Assume the required degree of consolidation (U_t), generally adopted as 90% but lower or slightly higher values are targeted in some circumstances.

2 Determine (u^*) using Figure C1. A c_v/c_h ratio needs to be assumed to obtain c_v. Unless results are available site specific, generally a value of 2 is assumed.

3 Find T'_h from:

$$T'_h = \frac{c_h t}{d_w^2} \qquad \text{. . . C1(1)}$$

4 Calculate

$$\gamma = -\left[\frac{8T'_h}{\ln\left(\frac{1-U_t}{u^*}\right)}\right] \text{ for surcharge fill} \qquad \text{. . . C1(2)}$$

5 Establish the diameter and permeability of the smear zone.

6 Determine ξ using Figure C2.

7 Calculate n from:

$$n = \exp(\alpha \ln \gamma + \beta) \qquad \text{. . . C1(3)}$$

where

$$\alpha = 0.3938 - 9.505 \times 10^{-4} \xi^{1.5} + 0.03714 \xi^{0.5} \qquad \text{. . . C1(4)}$$

and

$$\beta = 0.4203 + 1.456 \times 10^{-3} \xi^{2} - 0.5233 \xi^{0.5} \qquad \text{. . . C1(5)}$$

8 Calculate the influence zone:

$$D = n d_{\mathrm{w}} \qquad \text{. . . C1(6)}$$

9 Choose the drain pattern and determine the spacing of drain (D) from either:

$$S = \frac{D}{1.05} \quad \text{(triangular grid)} \qquad \text{. . . C1(7)}$$

or

$$S = \frac{D}{1.13} \quad \text{(square grid)} \qquad \text{. . . C1(8)}$$

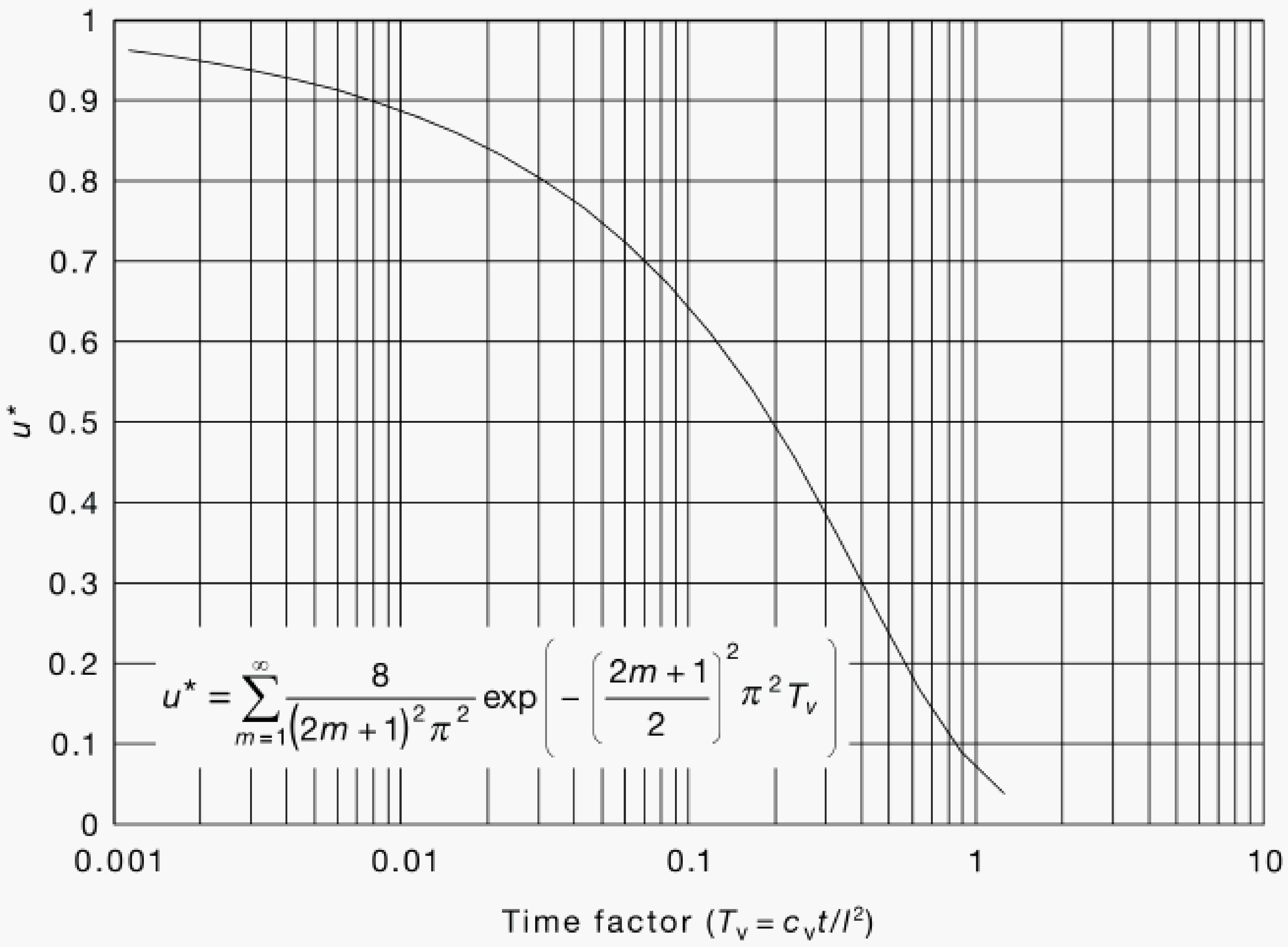


FIGURE C1 RELATIONSHIP BETWEEN T_{v} AND u^* (Ref. 86)

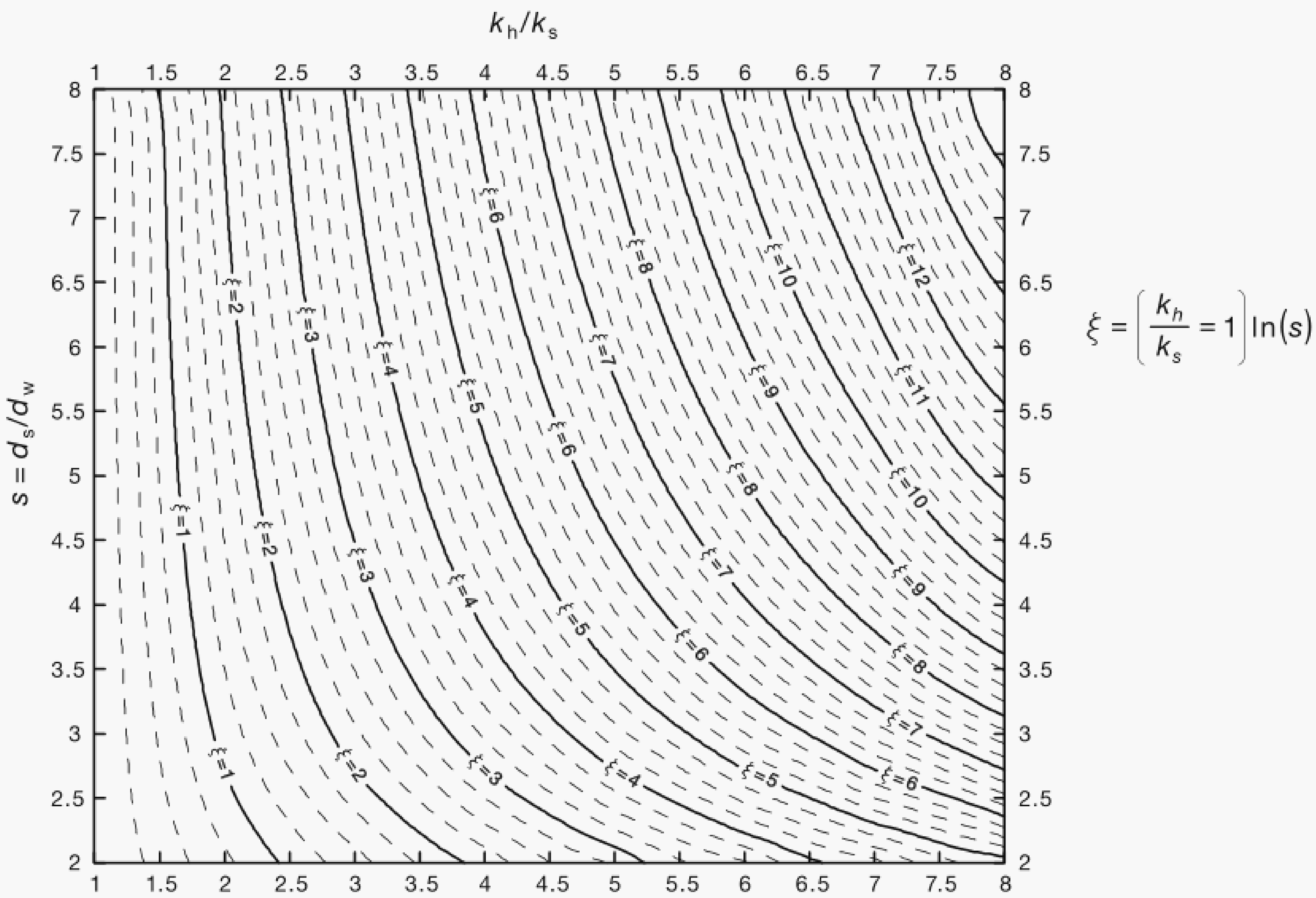


FIGURE C2 CONTOURS OF ξ (Ref. 86)

C2 WORKED-OUT EXAMPLE

The required soil parameters for the project are assumed to be:

U_t = 90%

l = 24 m

d_w = 34 mm

c_h = 2.5 m^2/year

c_v = 1.0 m^2/year

k_h/k_s = 5

S = 3

Maximum design surcharge, $\Delta\sigma$ = 120 kPa. Well resistance is neglected. Calculate the drain spacing (D), for t = 1.0 year.

Solution:

t = 1.0 year

1 $$T_v = \frac{1.0 \times 1}{24^2} = 0.002$$ . . . C2(1)

$$U_t = 0.9$$

2 Calculate u^* from Figure C1, hence

$$u^* = 0.95$$

3 $T'_h = \frac{c_h t}{d_w^2}$ . . . C2(2)

$= \frac{2.5 \times 1.0}{0.034^2} = 2163$

4 $\gamma = -\frac{8T'_h}{\ln\left(\frac{1-U_t}{u*}\right)} = -\frac{8 \times 2163}{\ln\left(\frac{1-0.9}{0.95}\right)} = 7686$

5 From Figure C2:

$\xi = 4.39$

6 Using Equations C1(4) and C1(5):

$\alpha = 0.463$

$\beta = -0.649$

7 From Equation C1(4):

$n = \exp(\alpha \ln \gamma + \beta) = \exp(0.463 \times \ln 7686 - 0.649) = 33$

8 Calculate D from Equation C1(6):

$D = nd_w$ . . . C2(3)

$= 33 \times 0.034 = 1.122$ m

9 Drain spacing = 1.1 m for triangular (1.122/1.05) or 1.0 m for square grid (1.122/1.13), respectively.

APPENDIX D

TEST STANDARDS

(Informative)

The relevant geosynthetic properties and associated test methods are as follows:

	AS	ASTM	CEN	ISO
Geotextile property				
Mass per unit area	AS 2001.2.13	D5261-92	EN 965	ISO 9864
Permeability/permittivity	AS 3706.9	D4491-99a	EN ISO 11058	ISO 11058
Pore size (dry sieving)	AS 3706.7	D4751-95		
Discharge capacity		D4716		ISO 12958
Sampling	AS 3706.1	D4354-99	EN 963	ISO 9862
Seam strength	AS 3706.6	D4884-96		ISO 13426
Tensile wide-width	AS 3706.2	D4595-01	EN ISO 10319	ISO 10319
Thickness nominal	AS 2001.2.15	D5199-01	EN 964	ISO 9863
Grab tensile strength	AS 2001.2.3.2	D4632		ISO 13934-2
Guide				
Durability	HB 154			ISO 13434

Abbreviations and explanations

AS Australian Standard

ASTM American Society for Testing & Materials

CEN European standard (to be reviewed every 5 years)

EN European standard (to be reviewed every 5 years)

ISO International standard (to be reviewed every 5 years)

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AS

2001 Methods of test for textiles

2001.2.13 Part 2.13: Physical tests—Determination of mass per unit area and mass per unit length of fabrics

3706 Geotextiles

3706.1 Part 1: Methods of test—General requirements, sampling, conditioning, basic physical properties and statistical analysis

ISO

9862:2005 Geosynthetics—Sampling and preparation of test specimens

9863-1:2005 Geosynthetics—Determination of thickness at specified pressures
Part 1: Single layers

9863-2:1996 Geotextiles and geotextile-related products—Determination of thickness at specified pressures
Part 2: Procedure for determination of thickness of single layers or multilayer products

9864:2005 Geosynthetics—Test method for the determination of mass per unit area of geotextiles and geotextiles-related products

10319:2008 Geosynthetics—Wide-width tensile test

11058:2010 Geotextiles and geotextile-related products—Determination of water permeability characteristics normal to the plane, without load

12958:2010 Geotextiles and geotextile-related products—Determination of water flow capacity in their plane

13426-1:2003 Geotextiles and geotextile-related products—Strength of internal structural junctions
Part 1: Geocells

13426-2:2005 Geotextiles and geotextile-related products—Strength of internal structural junctions
Part 2: Geocomposition

13434:2008 Geosynthetics—Guidelines for the assessment of durability

13934-2:1999 Textiles—Tensile properties of fabrics
Part 2: Determination of maximum force using the grab method

BS EN

963:1995	Geotextiles and geotextile-related products. Sampling and preparation of test specimens
964-1:1995	Geotextiles and geotextile-related products. Determination of thickness at specified pressures Part 1: Single layers
965:2009	Geotextiles and geotextile-related products. Determination of mass per unit area (all parts)
15237	Execution of special works. Vertical drainage

EN ISO

10319:2008	Geosynthetics—Wide-width Tensile Test (ISO 10319:2008)
11058:2010	Geotextiles and geotextile-related products—Determination of water permeability characteristics normal to the plane, without load (ISO 11058:2010)
HB 154	Geosynthetics—Guidelines on durability

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