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THE GUARANTEE OF THE QUALITY OF VERTICAL DRAINAGE SYSTEMS
LA GARANTIE DE QUALITE POUR LES SYSTEMES DE DRAINAGE VERTICAL
DIE QUALITÄTSSICHERUNG FÜR VERTIKALE DRÄNAGESYSTEME

Field measurements, executed on actual works with vertical drains, have shown a considerable variation in performance of these drains. As a consequence it was concluded that a quality control system for vertical drainage is required. Although vertical drains can also be constructed as sand drains, this paper deals with plastic drains only.
After a description of the functions of the vertical drain and the factors that affect them, specifications are given. A classification system is described first and the specifications given depend on the class of the current application. Finally execution aspects, such as field measurement systems, are shortly mentioned.

Wie Ergebnisse von Felduntersuchungen zeigen, wiesen vertikale Dränagesysteme erhebliche Qualitätsunterschiede auf. Daher hatte sich eine Qualitätssicherung als unumgänglich erwiesen. Dieser Bericht bietet ein System zur Sicherung der Qualität, das dem Verwender erlaubt, die Qualität tatsächlich zu überwachen.
Nach einer Funktionanalyse der Dränagesysteme wird beschrieben :
- Eine Klassifikation der Dränagesysteme, basiert auf den Entwurfsparametern;
- Qualitätsnormen für vertikale Dräns in bezug auf die Klassifikation;
- Empfehlungen für die Verlegearbeiten und für den vertikalen Drän selber;
- Systeme für Felduntersuchungen.

Die theoretischen Hintergründe, Laboruntersuchungsergebnisse und Felduntersuchungen werden gegeben und kritisch betrachtet.

1. FUNCTION ANALYSIS

1.1. Apart from the installation, both soil conditions and the quality of the drain play an essential role in the proper functioning of the system. The main purpose of the vertical drainage system is to accelerate the process of consolidation. The primary function of the drain is to absorb and transport ground water out of the surrounding layers with a relatively low entry resistance and high discharge capacity. The performance of the vertical drains during the desired period is closely connected to the soil conditions.

The following aspects are considered :
- Mechanical behaviour with respect to installation
- Mechanical behaviour with respect to soil deformation
- Filter behaviour
- Biological and chemical behaviour

1.2. Mechanical behaviour with respect to installation

Both before and during the performance of the draining function, the drain is exposed to external forces which can completely undo its effect if the admissable material stress is exceeded.
During the installation process, in which the drain is transferred from a dry environment (open air) to a very wet one (the ground), it is subject to tensile load. The extent of this tensile load depends, among other things, on the installation method (pushing, vibrating or jetting) and the care with which the work is carried out. With modern installation techniques the drain is often surrounded by a lance of steel that takes it to the desired depth. If this is done with a uniform speed, the resulting tensile load will probably not be high because practically the only resistance to be overcome is that of the guide rollers and the drain unreeling process. While moving from a relatively firm layer into a relatively soft layer the insertion speed may increase considerably. At this point the drain is exposed to an additional acceleration force, a compressive force, which may cause one or more components to break down, as has occured in practice.

1.3. Mechanical behaviour with respect to soil deformation.

Once in the ground, the drain can still be subject to substantial tensile forces as a result of differences in horizontal deformations over the length of the drain. The drain must be able to follow these deformations without breaking. This means that the drain should be capable of undergoing relatively high strains. The degree of tensile load induced by this phenomenon, therefore,depends on the elasticity modulus of the components of the drain.
Also, the drain will be compressed as a result of the horizontal soil pressure. This causes a reduction in flow profile and hence in discharge capacity. For the full non-woven drain this effect may be considerable because the filter envelope itself is compressed. With a composite drain with a profiled core, the filter will be pushed into the vertical discharge channels formed by the profile. The profiled core must also be resistant to compression. In vertical direction, displacement of the drain occurs due to the consolidation settlement of the soil layers. The drain will absorb this compression by bending at first locally, and, at a later stage, buckling. Buckling and compression of the drain may have a negative effect on the vertical water transport if the wrong transportation medium (core) is used.
These mechanical forces are mainly a function of the magnitude of the land fill H, the rate of filling dH/dt, the thickness of the compressible layers H_c and the relative settlement s/H_c.

1.4. Filter behaviour

The function of the filter is to retain soil particles and to allow pore water to flow with as little hydraulic resistance as possible. The demands made upon a filter are in fact contradictory, since the less permeable the filter is to particles, the greater will be its hydraulic resistance. The choice of the filter will always be a compromise between water permeability and soil tightness. Blocking of the filter by soil particles obstructs the inflow capacity of the drain and hence causes the system to malfunction.
The movement of soil particles is caused by erosion, a process that depends on the sensitivity of the soil, the hydraulic gradient and the presence of cracks in the soil. The sensitivity to erosion of cohesive soil depends on the colloidal cohesion forces between the soil particles. For clay, the forces between the particles are determined by the type of clay mineral, the adsorbed ions on the clay surface and the composition of the pore water. It appears that sensitivity to erosion increases in the order kaolinite, illite and montmorillonite, decreases with increasing electrolyte concentration and decreasing quantity of interchangeable sodium.
Whether a particle erodes or not is a question of balance between the cohesion and hydraulic forces. Immediately after laying a layer of land fill, the hydraulic gradient and therefore the shear stress on the particles around the drain, can increase considerably.

The presence of small cracks in the soil skeleton, that may be caused during installation and/or exist due to vegetative residuals, can stimulate erosion.
Once a soil is eroded, it will be carried away by the groundwater flow and, depending on the balancing of forces, it will deposit, settle out, stay in suspension, or be carried away completely. Deposits in front of or against the filter may cause a very poorly permeable filter cake, whereas deposit within the filter itself may result in partial or total clogging of the filter pores.

Another aspect of the permeability of the system is the remoulding and redistribution of the soil around the drain as a result of the insertion of the lance. When the lance is inserted it pushes aside its own volume, and the surrounding soil will be drawn downwards according to the direction of the friction.
When subsequently the lance is pulled out the friction will act in an upward direction. This may cause sand lenses to spread, especially in strongly stratified soil. By this, the permeability of the soil around the drain may decrease.

1.5. Biological and chemical behaviour

Apart from physical influences on the durability and quality of the vertical drainage system, there are also biological and chemical effects to be considered. An example of the latter is the desintegration of synthetic material. In this respect, the life span of the drain materials should be equated to the period during which the drain is required to function properly.
In general it can be stated that, with the usual penetration depth of vertical drains, the microbiological activity is of minor importance due to the lack of oxygen.

2. CLASSIFICATION SYSTEM

Based on a classification system and the results of the soil investigation, the designer must be able to determine the category of the project and the specific demands of the vertical drains.
The classification system consists of design parameters which refer to geometry and time. These parameters,

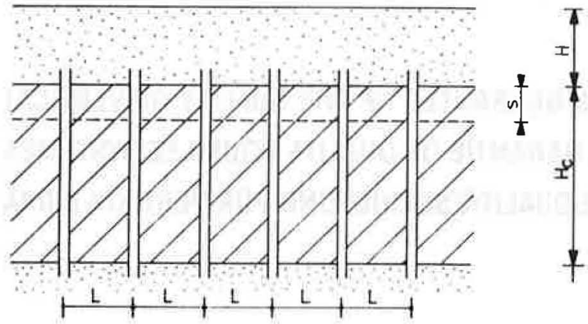

Figure 1 Design parameters of the classification system

corresponding with factors that influence mechanical behaviour and filter action, are explained in Figure 1.

- The settlement s(m) can be deduced from soil and laboratory investigation using soil mechanical calculations. In relation to the thickness of the layer H_c(m), the relative settlement s/H_c(%) is a direct indication of the compressibility of the subsoil.

- The thickness of the layer H_c(m) together with the excess pore pressure determines the total horizontal pressure on the drain.

- The depth of the land fill H(m), together with the rate of land fill dH/dt(m/s), and the permeability of the soil, determine the degree of excess pore pressure.

- The consolidation time, T_{90}(s), follows from soil mechanical calculations.
  In relation to the drain spacing L(m), T90(year) gives an indication of the permeability. From settlement s, combined with the extent of the excess pore pressure, information can be obtained about the water discharge capacity of the drain.
  By means of a conversion factor, as described by Kremer et al (1), a comparison of data from different projects can be made.

- The erosion of particles depends on the given soil condition and the quantity of ground water flow.

On the basis of these parameters, the classification schedule as shown in Figure 2 is drafted.

3. DRAIN SPECIFICATIONS

3.1. Specifications have been formulated for prefabricated plastic drains to promote greater functional reliability of vertical drainage systems. Quality criteria have been formulated for several drain properties based on the factors affecting the system, current investigation methods and, last but not least, many years practical experience.

3.2. Stress-strain behaviour of the complete drain

To prevent damage to the drain during installation, it should be resistant to the strains and forces caused by the accelerations occuring.
The actual strains must retain within certain limits in order to ensure that the drain is more or less unstressed and has the required length and bore when placed into the ground.
On the basis of calculations, similar failure criteria have been established for all classes:

			$s/H_c \leq 15\%$						$s/H_c > 15\%$			
			$H_c \leq 10$ m		$H_c > 10$ m		$H_c \leq 10$ m		$H_c > 10$ m	
T_{90} (L = 2.50 m)			$\geq$ 1.5 year	< 1.5 year	$\geq$ 1.5 year	< 1.5 year	$\geq$ 1.5 year	< 1.5 year	$\geq$ 1.5 year	< 1.5 year
H $\leq$ 2.50 m	dH/dt	not relevant	1.1 A1	1.2 A1	1.3 B1	1.4 B2	1.5 A1	1.6 A1	1.7 B2	1.8 B2
H $\leq$ 2.50 m	dH/dt	$\leq$ 0.75 m/month	2.1 A1	2.2 A1	2.3 B1	2.4 B2	2.5 A1	2.6 A1	2.7 B2	2.8 B2
H $\leq$ 2.50 m	dH/dt	> 0.75 m/month	3.1 B1	3.2 B2	3.3 C2	3.4 C2	3.5 B1	3.6 B2	3.7 C2	3.8 C2
H > 2.50 m	dH/dt	not relevant	4.1 B1	4.2 B1	4.3 B1	4.4 B1	4.5 B1	4.6 B1	4.7 C1	4.8 C2
H > 2.50 m	dH/dt	$\leq$ 0.75 m/month	5.1 B1	5.2 B1	5.3 B1	5.4 B1	5.5 B1	5.6 B1	5.7 C1	5.8 C2
H > 2.50 m	dH/dt	> 0.75 m/month	6.1 B1	6.2 B1	6.3 C2	6.4 C2	6.5 B1	6.6 B2	6.7 C2	6.8 C2

Figure 2 Classification schedule

- strain at failure at least 2 %
- force at failure at least 0.5 kN
- with a force of 0.5 kN, the strain shall be less than 10 %.

The strain and the force, mentioned above refer to the weakest elements of the drain, i.e. the core and filter or the glued butt joint.
The stress-strain behaviour is determined using a uniaxial tension test with a constant tension rate.

3.3. Stress-strain behaviour of the filter material

During the functioning period of the drain, the wet filter must not yield, or be pushed completely into the core profile. In order to satisfy this condition, the filter, in a wet environment, has to be resistant to the strains and forces, caused by the total horizontal pressure on the filter. On the basis of calculations, the classes have been divided into three main categories, for which criteria have been formulated. These criteria are given in Table 1 and Figure 3. The stress-strain behaviour is deduced from a biaxial tensile test, that represents the actual force-deformation behaviour of the wet filter material. In this test, a sample of the filter material is tensioned in transverse direction at a constant rate. Longitudinal deformation of the filter material is prevented. It turns out that the stress-strain behaviour of the filter varies greatly with the type of tensile test. The biaxial tension test described in particular shows a much more rigid behaviour with on one hand, a lower breaking strain, and on the other, a considerably higher breaking strength.

3.4. Filter quality

At present it is difficult to formulate a complete filtration theory because of the variety of phenomena involved and the large number of parameters. In current practice a simplified approach is used for granular filters and geotextiles, based on considering two criteria, established separately by neglecting other phenomena and parameters : the permeability criterion and the filtration or retention criterion. This simplification is also used as an approach to the filter quality of synthetic drains for lack of sufficient available knowledge and information.
The water that flows through the ground towards the vertical drain has to pass through the filter with as little resistance as possible. The permeability criterion is defined as a minimum value for the permittivity of a contaminated filter in the soil. For all classes, a minimum value of 0.0003 1/s is suggested.
A testing method by which the filter is flushed with a clay suspension, is being developed for determining this resistance. This test is taken to be more in correspon-

Table 1 Quality criteria for the wet filter material

Criteria	Category		
	A	B	C
ε_f (%) $\geq$	2	2	2
σ_f (kN/m²) $\geq$	1.2 - 0.1 ε	2.4 - 0.2 ε	3.5 - 0.25 ε
σ_2 (ε_n = 5%) (kN/m²)	0.7	1.4	2.25

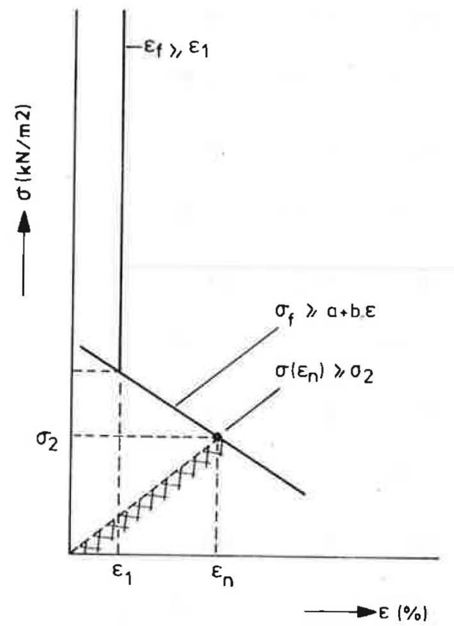

Figure 3 Quality criteria for the wet filter material

dence with reality than a test, in which the filter is flushed with water.
What remains to be investigated are the rates of flow in relation to the particles in the suspension, the particle size distribution and the type of clay to be applied.
To define a value for the retention criterion is much more difficult. The need for adequate permeability leads inevitably to particles eroded from the ground and slipping through the filter with the ground water. These particles will attach themselves to the core material, will settle or will be carried along with the water flow. In the first two cases, this can lead to a reduction of the discharge capacity of the drain. When particles attach to the material, Van der Waals-forces and electrostatical forces play a part. There is no information on the sensitivity of the drain material to the soil particles, the chemico-physical composition of the ground water etcetera. Whether particles settle in the core depends on the rate of flow in the drain and the size and specific mass of the particles carried along. Since in this case the particles are small, the rate of settlement can be calculated with Stokes Law. The rate of flow of the water in the drain depends on the rate of the consolidation settlement, the diameter of the core, the distance between the drains and the discharge of the drain water to underlying and/or overlying ground layers. On the basis of practical experience, acquired in a large number of drain projects, it is understood that soil particles larger than 0.02 mm can severely impede discharge of water as a result of settlement. In view of the many parameters influencing the filter mechanism, however it is not justified to prevent soilparticles up to 0.02 mm from entering the drain.

Also in anticipation of the results of investigations still in progress, it is suggested that 90 % of the holes in the filter shall be smaller than 0.12 mm.

3.5. Discharge capacity

The discharge capacity as a function of the horizontal pressure on the drain is determined with the following test. A stretched drain is flowed with different discharges at different pressures perpendicular to the flow of water. The drop in waterhead over the drain is measured. The discharge capacity is defined as the discharge by the hydraulic gradient.
Each main category of the classification system is divided into two subcategories for which criteria are defined as shown in Table 2.
Another aspect with respect to the discharge capacity is the folding and buckling of the drain due to the consolidation settlement of the soil, especially in the case that s/H_c exceeds 15 %.
The discharge capacity of a folded drain must exceed or be equal to 75 % of the capacity given for the stretched drain.
The flow test to determine the discharge capacity is identical to that for the stretched drain, on the addition that the sample, with a length of 400(±4)mm, is buckled three times in the middle, over a length of 100(±1)mm: one buckle of 180° in the middle and two buckles of 90° on both sides at a distance of 50(±0.5)mm. The sample now having an effective length of only 300 (±3)mm, is then placed in the drain tester.

4. EXECUTION OF DRAIN JOBS

4.1. Storage and transport

Practice has shown that installation, storage and transportation methods may affect the quality of the drain. In particular, temperature, humidity and UV-radiation are important factors. The glued seam needs special attention, since it can be sensitive to extreme temperature.

4.2. Measuring systems

Measuring systems are suggested for surface stability and consolidation time.
The critical stage as regards the surface stability is when the surcharge is being applied. During the elevating stage, pore pressure will increase with each land fill, while the effective stress does not change, causing the stability safety level to drop. This danger can be recognized by excessively high pore pressures, and excessive ground level movements at the toe of the slope of the elevation.
Quality control is less crucial with regard to the consolidation time. Whether the desired degree of consolidation will be attained within the planned period can be checked by comparing actual settlements and pore pressures with calculated values.
Horizontal and vertical soil deformations are measured by aiming and levelling markers or pickets. Pore pressures are measured using pore pressure transducers, or open standpipes if the rate of ascent is relatively low.

Table 2 Quality criteria for the discharge capacity

	main category	A		B		C	
	subcategory	1	2	1	2	1	2
Test	discharge (m^3/s)	5.10^{-6}	5.10^{-6}	5.10^{-6}	5.10^{-6}	5.10^{-6}	5.10^{-6}
	pressure (kN/m^2)	150	150	250	250	350	350
Criterion	required discharge capacity (m^3/s)	25.10^{-6}	50.10^{-6}	25.10^{-6}	50.10^{-6}	25.10^{-6}	50.10^{-6}

A further check on the consolidation process can be made using discharge measurements. Collecting the water from the drain is the most direct method of showing the effectiveness of the drainage system. With this method it is essential, however, that the discharge through the drain occurs upwards only.
Although in principe the above measurements are relatively simple and cheap, the application of a particular measuring system will be determined by the size of the work and by the risks involved with a malfunctioning drainage system.

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