HYDRAULIC RESISTANCE OF STEEL SHEET PILE JOINTS

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ABSTRACT: Steel sheet pile joints are investigated to determine their permeability behavior. A suitable definition is obtained for the permeability. A testing rig is described and tests on 10 different joint filler materials are reported. The results show significant time-dependent and joint-dependent features. These are explored and conclusions on both water swelling and bituminous materials are noted. A case study gives a design example as well as suggestions on how a safety factor can be implemented.

INTRODUCTION

The quantification of seepage ground-water flow through the joint of steel sheet piles has practical relevance for the design of retaining walls. Examples are building pits—these are temporary structures—and containment systems, vertical barrier systems for waste disposal and landfill purposes, roads in excavation, which have a more permanent character. Generally speaking the joints between sections of the wall are sealed with a filler material and the resistance to seepage is a function of the type of material employed. The soil mechanical design of retaining walls has received ample attention in the past, see *EAU* (1990), chapter 8. This paper only focuses on the permeability aspects.

The aim of this paper is to review a comprehensive design methodology. To begin with suitable material parameters are defined to describe the phenomenology of the seepage process through the joints. Then an experimental setup is detailed to measure the material parameters. The experimental results display a certain scatter; the underlying cause of this is explored and discussed. A wide range of materials are tested and the results are shown. Finally, a case study is presented.

For all practical purposes the flow through the joints and surrounding soil medium can be regarded as laminar. Thus, Darcy's law in isotropic form [Bear (1978)] is used to describe the soil seepage process

$$q_i = -k\frac{\partial \varphi}{\partial x_i} \tag{1}$$

The equation of continuity reads

$$\frac{\partial q_i}{\partial x_i} = 0 \tag{2}$$

The flow through the joints obeys a simple resistance formula

$$\Delta\varphi = Rq \tag{3}$$

The resistance R = homogenized value over many joints (see following section).

When the flow is laminar it transpires that, in many cases, R depends on the applied pressure due to various physical effects, such as the presence of debris or air bubbles and a pressure-dependent joint filling behavior. This gives rise to nonlinearity in the analysis of practical problems. A further discussion is presented in the section titled "Experimental Work."

THEORETICAL CONSIDERATIONS

In a practical situation the sheet pile is positioned between two media, with different permeabilities k_1 and k_2, as shown in Fig. 1. The joints in the piles have horizontal spacings, b. Leakage occurs only through the joints; the sheet piles themselves are impermeable. A one-dimensional description is applied in the x direction. The pressure field is averaged over many joints in the y direction, perpendicular to the plane of the figure. The averaged pressure behaves smoothly

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through a transition zone, with a thickness of the order of $1/2b$ on either side of the pile. The exact shape of the pressure curve in the transition regions is not known. Outside these zones the pressure varies linearly according to Darcy's law.

The variation of pressure in the transition zones gives rise to analytical problems that are beyond the scope of this paper [a method analogous to the one adopted by Koenders and Williams (1988) needs to be modified to give the required insight]; an idealized description, which preserves the physical reality of the transition effect, is pursued. In the idealization, represented by the dashed lines in Fig. 1, the pressure gradient jumps at $x = \pm\delta$. Both the pressure head φ and the discharge q_x are continuous at these points. The constitutive equations are

$$\left.\begin{array}{ll} q_x = -k_1 \dfrac{\partial\varphi}{\partial x}; & x < -\delta \\ q_x = -k_2 \dfrac{\partial\varphi}{\partial x}; & x > \delta \end{array}\right\} \quad \varphi(-\delta) - \varphi(\delta) = Rq_x \tag{4}$$

Because of the averaging it is appropriate to normalize R on the distance between the joints

$$\rho = \frac{b}{R} \tag{5}$$

where ρ = inverse specific resistance. For a given flow $q_x = q_0$ through the system, the pressure field becomes

$$\varphi = \varphi_0 - q_0 \left\{ \frac{x + \delta}{k_1} - \frac{b}{2\rho} \right\}, \quad x < -\delta; \qquad \varphi = \varphi_0 - q_0 \left\{ \frac{x - \delta}{k_2} + \frac{b}{2\rho} \right\}, \quad x > \delta \tag{6a,b}$$

A reference level φ_0 is added. It is observed that the role of δ is irrelevant when

$$\delta << \frac{k}{\rho} b \tag{7}$$

Some practical values are substituted to determine the range for which this condition is valid. For sand or gravel $k \sim 10^{-6}$–10^{-3} m/s. It will be shown that $\rho \sim 10^{-12}$–10^{-9} m/s. As b is of the order of 1 m, it follows that a δ smaller than 1 m is adequate. The value of δ is estimated from the effective path length a water particle needs to travel to traverse the joint. A joint cross section is depicted in Fig. 2. The route is indicated from AB to CD.

However, for $k \sim \rho$, that is when the permeability of the soil and effective permeability of the sheet pile system are of the same order of magnitude, δ becomes relevant and a more detailed calculation of the transition zone is necessary. In the remainder of this paper it will be assumed that $k >> \rho$.

EXPERIMENTAL WORK

To measure the joint leakage of a sheet pile wall a test setup was built. The setup consists of a square building pit, the walls of which are covered with single sheet pile sections. These sections are hot-rolled, U-shaped, L 2N sections 6.5 m long and 400 mm wide. They are driven into a deposit of boulder clay, to the required depth, by a vibratory method. Each side of the pit takes 11 sheet pile sections; thus, the pit's dimensions are 4.4 × 4.4 m².

On top of the impermeable clay a 3-m thick layer of sand and gravel is present, forming the stratum in which the tests were performed. This permeable layer is in turn covered by a sandy

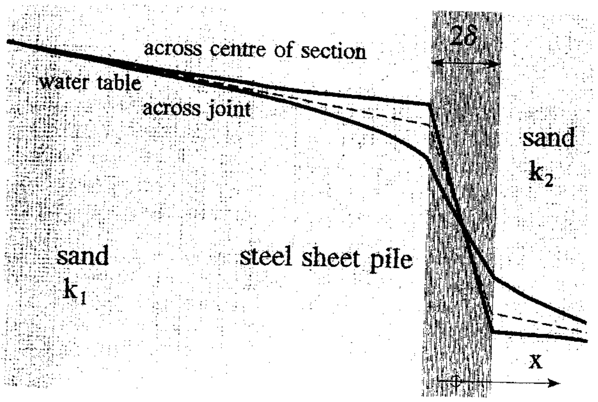

FIG. 1. Head around Steel Sheet Pile

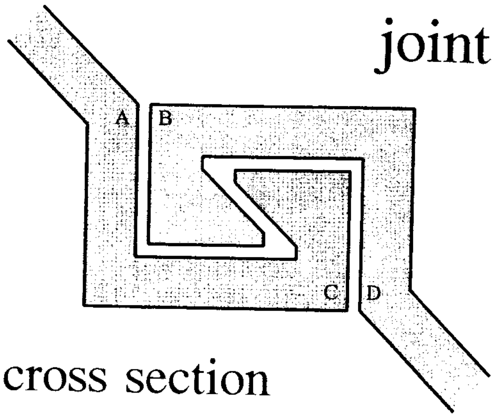

FIG. 2. Joint Cross Section

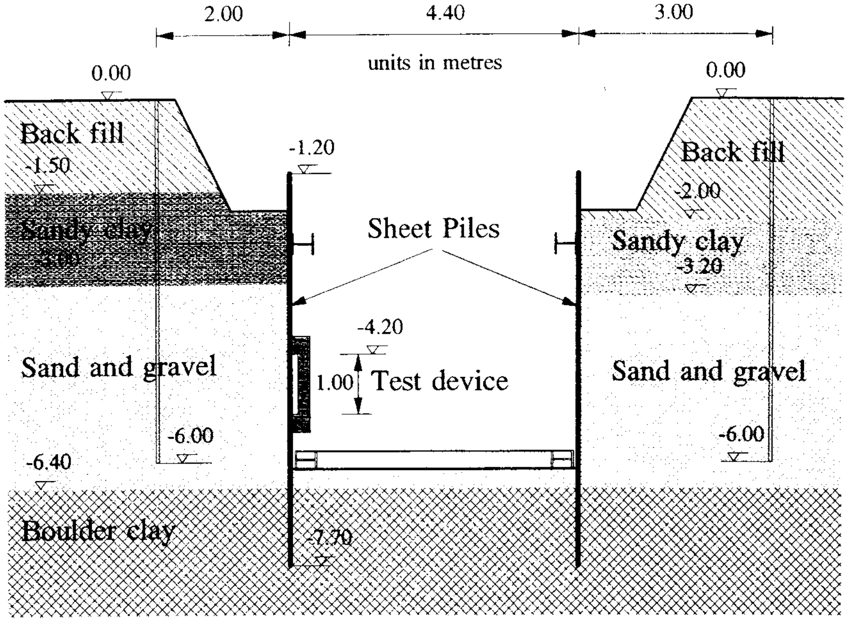

FIG. 3. Cross Section of Test Pit

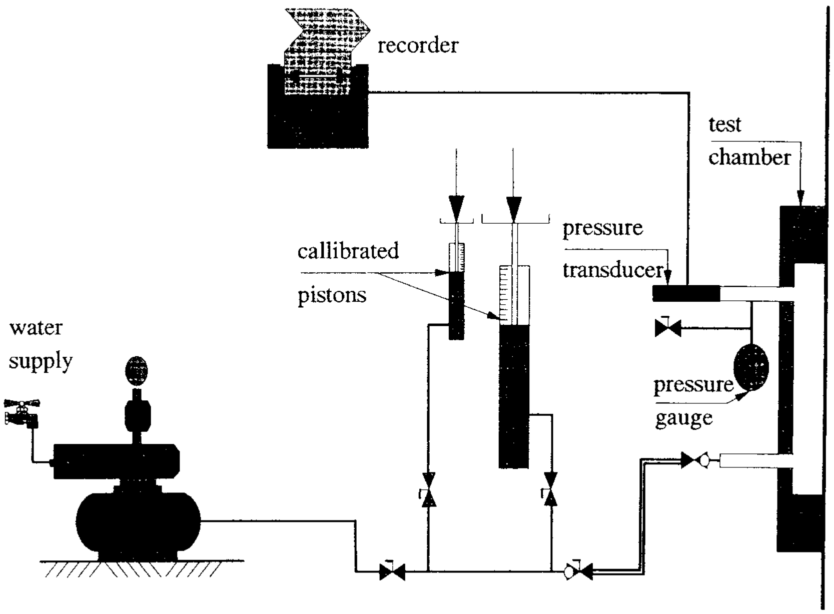

FIG. 4. Test Setup

clay on top of which a backfill reaches up to ground level. The complete soil profile is depicted in Fig. 3.

During the driving process unwanted debris is removed from the joints by using a profiled peg at the base of the next empty joint. The vast majority of the joints is filled with a sealing material, inserted before driving according to the manufacturers' specifications; some are left empty for reference purposes. Every sealing material is applied to more than one joint, so that results of tests on joints with the same filler material can be compared.

When this procedure is completed the pit is excavated to a depth of 4.9 m below the top of the wall. To control the horizontal deformation of the wall, wailings are installed at two levels. A cross section of the pit and the sheet pile wall is given in Fig. 3. The water level outside the pit is monitored at two positions to ensure that it does not interfere with the test device.

To conduct a test on one type of joint filler material a special box structure is deployed to cover one joint over a height of 1 m, forming a chamber with watertight seals against the sheet pile sections. During the test this chamber is filled with water at an adjustable pressure. The seepage rate through the joint section is measured. This rate may vary over a wide range from about 10^{-2} m^3/hr for entirely empty joints to 10^{-8} m^3/hr for sealed joints, imposing special requirements on the measurement acquisition system and measurement gauges. This aspect of the test setup is illustrated in Fig. 4.

Vertical seepage through the joint parallel to the sheet pile sections is inhibited by injecting the joint space above and below the pressure chamber with a waterproof material.

The pressure in the test chamber is monitored with an appropriately positioned pressure gauge; in addition, the pressure is measured with a pressure transducer device and recorded continuously for later analysis. The measurement of the seepage is carried out by means of a calibrated piston. A dead weight on the piston ensures a constant water pressure in the system during the testing period.

At fixed intervals during the test the volume of the cylinder below the piston is determined. The volume decrease per unit time yields the average seepage rate for a particular time interval. Tests under steady loading conditions are conducted for up to 24 hr or longer; these tests are carried out consecutively, at different pressure levels for each joint.

During the tests minor pressure fluctuations are observed. Special provisions are made to exclude the formation of air bubbles, both in the joints and in the water supply system, which are disruptive to the proper conduct of a test and notably affect reproducibility. However, it transpires that this phenomenon cannot be entirely eliminated.

Values for ρ are defined by putting relations (3) and (5) together

$$\rho = \frac{bq}{\Delta\varphi} \tag{8}$$

where q = specific discharge, so bq = discharge per joint height, which is measured; $\Delta\varphi$ = head difference, obtained from the adjustable pressure in the test chamber and the difference of position between the piston and the chamber's center.

The measurement accuracy is dominated by the visual reading of the water level in the piston. The accuracy is 0.5 mm and this must be kept in mind for a consistent interpretation of the results. To put this number in context, consider (8) $\Delta\varphi$ = 10 m and $\rho = 10^{-10}$ m/s; the discharge would then be 28,800 mm^3 in 8 hr. As the piston cross section is 2,027 mm,^{2} two subsequent readings may lead to an error of 2,027 mm^3 of discharge, which is approximately 7%.

Fig. 5 shows a typical result of a series of measurements. These measurements are for a joint filled with a water-swelling material, tested at various pressure differences across the joint. The order of magnitude of the measurement error is of the order of half the size of the pressure marker symbols. A characteristic feature of the seepage behavior is that the permeability of the joint decreases as a function of time. This effect is found for nearly all joints no matter what the filler material is. It may partly be associated with a relatively minor rearrangement of the filler material in the joint (water-swelling materials may continue swelling), and may partly be due to the collection of small pieces of debris in the pores of the joint; even small air bubbles may have played a similar role. The collapse of air bubbles under pressure is discussed by Theunissen (1982). Due to the size of the pores in the joint filler material it is unlikely that, at relevant pressures, bubble collapse may have accounted for variations in permeability for sealed joints; however, bubble collapse may well have played an important role in the case of open joints.

A second phenomenon, clearly observed in the test result of Fig. 5, is that the permeability of the joint is an increasing function of the applied pressure difference. Mechanical rearrangement of the distribution of the filler material in the joint is probably responsible for this effect,

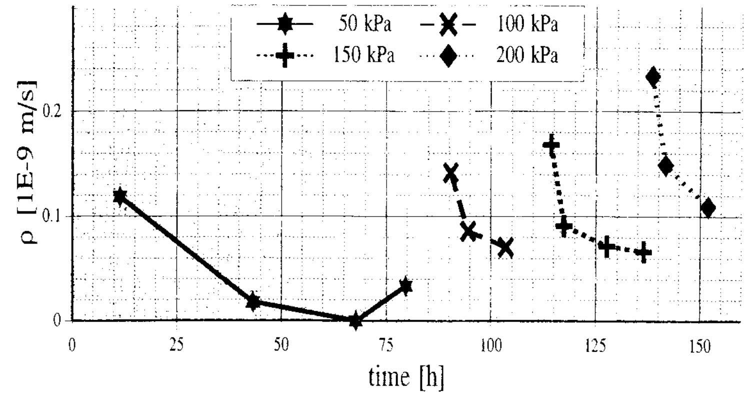

FIG. 5. Test Result for Well-Embedded Filler Material

because such a redistribution would be pressure dependent; in other words, for increased pressure, certain pores would open up that would otherwise be shut.

EXPERIMENTAL RESULTS

In addition to a test on an unfilled joint, two types of filler substances were tested; bituminous materials and water swelling materials. The brands are summarized in Table 1. (In Table 1 the products are collected according to the type of material only. No specific properties, with respect to driveability or ambient temperature and moisture, are distinguished.) The seepage through joints filled with these materials was measured over a period of 24 hr at various pressures. The seepage resistance per unit length has an average value over this period, but also has a substantial variation. Obviously the individual joints do not all behave in the same manner because of the manufacturing process. Thus there are two sources of variation, the first associated with time dependent effects and the second with mechanical differences of the joints.

To report the variation in test results two numbers need to be specified: a standard deviation obtained from the readings of one joint as a function of time, and a standard deviation derived from the time-averaged readings of separate joints. These two numbers are called σ_t and σ_j. Since permeability exhibits a lognormal distribution, they are most conveniently expressed as factors of the relevant lognormal averages and are termed factors of variation. In this way various filler materials can be compared using the following three criteria:

- The lognormal average joint permeability (inverse specific resistance)
- The factor of variation associated with time-dependent variation
- The factor of variation associated with joint deviation

These results, as a function of the applied pressure difference, are summarized in Table 1. Some measurements consist of readings at fewer than three time points; these are denoted by a superscript "a." Also shown are averages and relative standard deviations of the two groups of materials used.

The following conclusions may be drawn after scrutinizing Table 1.

- The bituminous materials as a group are more pressure sensitive than water-swelling materials as a group.
- The water-swelling materials as a group show slightly more time-dependent variation than bituminous materials.
- The water-swelling materials are generally less permeable than bituminous materials.
- For all materials the variation associated with joint variability is more or less the same.
- Erratic behavior is a typical feature of these materials, but the average permeability is three orders of magnitude less than an empty joint.

CASE STUDY

The total amount of water seeping into a building pit with dimensions similar to those outlined in the previous section is assessed. The specific discharge is obtained from (3) and (5)

TABLE 1. Lognormal Averaged Inverse Joint Resistance Together with Factors of Variation

	50 kPa			100 kPa			150 kPa			200 kPa		
Material	$\bar{\rho}$	σ_j	σ_t	$\bar{\rho}$	σ_j	σ_t	$\bar{\rho}$	σ_j	σ_t	$\bar{\rho}$	σ_j	σ_t
(*a*) Bituminous filler material												
Beltan	$6.98\ 10^{-11}$	21.28	5.36	$1.31\ 10^{-09}$	62.06	1.25	^{a}	^{a}	^{a}	$1.93\ 10^{-08}$	^{a}	2.23
Cariphalte	$7.83\ 10^{-11}$	4.79	3.77	$3.72\ 10^{-10}$	6.06	1.65	$2.82\ 10^{-10}$	6.75	1.50	$1.24\ 10^{-10}$	1.84	1.69
LRCCP 2 (T1274)	$1.75\ 10^{-10}$	8.04	3.02	$4.66\ 10^{-10}$	2.36	1.10	$5.13\ 10^{-10}$	1.64	1.04	^{a}	^{a}	^{a}
LRCCP 13 (T1295)	$2.06\ 10^{-11}$	6.52	4.87	$1.23\ 10^{-10}$	2.99	1.14	$1.89\ 10^{-10}$	1.99	1.25	$5.52\ 10^{-10}$	3.73	1.24
Tixophalte	$1.80\ 10^{-11}$	16.45	3.35	$8.59\ 10^{-11}$	6.22	1.22	$1.40\ 10^{-10}$	8.16	1.16	$6.77\ 10^{-11}$	2.59	1.12
Eurolan	$2.62\ 10^{-10}$	6.56	2.49	$2.33\ 10^{-09}$	17.62	1.53	$3.33\ 10^{-10}$	1.19	1.25	$2.74\ 10^{-10}$	^{a}	1.26
Bitume Special	$9.01\ 10^{-11}$	5.78	1.90	$2.06\ 10^{-10}$	6.38	1.31	$2.67\ 10^{-10}$	1.75	1.65	$4.38\ 10^{-10}$	9.03	1.17
Average	$7.02\ 10^{-11}$	2.72		$3.80\ 10^{-10}$	3.34		$2.56\ 10^{-10}$	1.52		$4.93\ 10^{-10}$	6.13	
(*b*) Water-swelling filler material												
Adeka P 201	$2.39\ 10^{-11}$	7.78	3.62	$2.35\ 10^{-11}$	6.75	2.47	$1.56\ 10^{-11}$	2.83	3.19	$1.63\ 10^{-11}$	2.91	3.14
Adeka KCH 2003 T	$5.01\ 10^{-11}$	2.77	2.46	$1.58\ 10^{-10}$	1.55	1.54	$1.67\ 10^{-10}$	1.79	1.30	$9.45\ 10^{-11}$	2.03	1.83
Chemiguard	$4.29\ 10^{-11}$	14.34	1.07	$4.45\ 10^{-11}$	4.28	1.51	$5.05\ 10^{-11}$	4.89	1.27	$9.23\ 10^{-11}$	6.45	1.30
Average	$3.72\ 10^{-11}$	1.48		$5.49\ 10^{-11}$	2.64		$5.09\ 10^{-11}$	3.27		$5.22\ 10^{-11}$	2.74	

$$q = \rho \frac{\Delta\varphi}{b} = \rho \frac{h - y}{b} \tag{9}$$

where h = height of the free water table above the bottom of the pit; and y = vertical position. The discharge on aggregate Q is obtained by integrating (9), with respect to y, and multiplying the result by the pit's circumference, L

$$Q = \rho \frac{h^2 L}{2b} \tag{10}$$

The discharge appears to be of the order of 5 L per day, for the following set of parameters: $h = 5$ m; $b = 0.4$ m; $L = 17.6$ m; and $\rho = 10^{-10}$ m/s. The choice of filler material is relatively insensitive as the pressure difference is limited. This only concerns the seepage; several other principles are to be considered. Pumping capability should be designed to within a safety factor; 2 to 4 for a realistic case (temporary structure) and 4 to 8 for a safe case (permanent structure).

The performance of a sheet pile wall compares favorably with an alternative structure, such as a slurry wall [see Franzius et al. (1992)], even when variability due to construction factors are accounted for.

CONCLUSIONS

Sheet pile walls with sealed joints are deployed as an effective means of semipermeable protection. The type of sealing is marginally unimportant for low pressure differences (<50 kPa), but for higher pressures (>100 kPA) water-swelling materials perform more consistently and generally possess a lower permeability. Tests show that both a time-dependent and a joint-dependent variation are present, causing a degree of scatter in the outcome of calculations. The latter was analyzed and appears to be a factor of the order of magnitude of 3, on aggregate. A safety factor is recommended.

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APPENDIX II. NOTATION

The following symbols are used in this paper:

b = joint distance (m);
h = height free water table (m);
k = permeability (m/s);
L = circumference (m);
Q = discharge (m^3/s);
q = specific discharge (m/s);
R = resistance (s);
x = horizontal position (m);
y = cross-sectional position (m);
ρ = inverse specific joint resistance (m/s);
φ = pressure head (m); and
2δ = joint effective path length (m).