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Performance of H-jointed steel pipe sheet piles with H-H joint in vertical hydraulic cutoff walls

Performances des rideaux de palplanches avec des joints type H-H dans les parois hydrauliques verticales

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ABSTRACT
This paper shows potentials of developed H-jointed SPSP and proposed H-H joint for application as a vertical hydraulic cutoff wall in coastal landfills. Their construction accuracy, resistance characteristic under lateral load, joint performance, and hydraulic conductivity are assessed through experiments. H-jointed SPSP can control the accuracy of construction and exhibits higher lateral bearing capacity than SPSP with traditional joint connections. H-H joint demonstrates larger tension resistance than traditional joint. Hydraulic conductivity of 10^{-8} cm/s is proposed for use in design of H-H joint. The H-jointed SPSP with H-H joint is recommended as a hydraulic cutoff wall in coastal landfills.

RÉSUMÉ
Cet article montre les potentialités des rideaux de palplanches avec des joints type H-H utilisés en tant que parois verticales hydrauliques dans les centres de stockage côtiers. La précision de leur construction, leur résistance sous chargement latéral, la performance de leur joint et leur perméabilité sont évaluées expérimentalement. Les rideaux de palplanches avec des joints type H-H peuvent contrôler la précision de la construction et montrent une capacité portante latérale plus élevée que les rideaux de palplanches avec des joints traditionnels. Les joints de type H-H montrent une résistance à la traction plus grande que celle des joints traditionnels. Une perméabilité de 10^{-8} cm/s est proposée pour le dimensionnement des joints de type H-H. Les rideaux de palplanches avec des joints type H-H sont recommandés en tant que parois verticales hydrauliques dans les centres de stockage côtiers.

1 INTRODUCTION

Steel pipe sheet pile (SPSP) consists of a steel pipe and couplings welded on either side of the steel pipe. One SPSP is connected to the next one by interlocking their couplings; the interlocked couplings form a joint. The most commonly used joints are the P-P, P-T, and L-T; the L, T, and P refer to angle steel, T-steel, and circular pile, respectively. These joints shall be referred as "traditional joints" in this paper. Until now, SPSPs are widely used in construction of bridge pier foundations and earth retaining walls. In the field of waste management, application of SPSP as a vertical cutoff wall in coastal landfill sites has been reported in recent years, its adoption is mainly because of their construction accuracy and economic efficiency. However, various issues on mechanical and hydraulic characteristics of the traditional joints in SPSP need to be addressed, especially, the critical points such as their low rigidity, the rather low construction accuracy, and inadequate hydraulic conductivity.

The authors have introduced a number of technologies with respect to SPSP joint sections aimed at improving their performance and widening their application areas. They have developed a new H-joint from a simple idea in which two steel pipe piles are connected by H-steel section welded on them to form what is known as "H-jointed SPSP" (Kimura et al., 2003). In order to improve the performance of the H-jointed SPSP, the authors introduced yet another joint referred to as the "H-H joint" to alternate with the H-joint; it is formed by interlocking two H-steel sections of different sizes.

This paper discusses the potentials of H-jointed SPSP and H-H joint for application as a vertical hydraulic cutoff wall in coastal landfills. Their construction accuracy, resistance characteristic under lateral load, joint performance at the corner part of a vertical cutoff wall, and hydraulic conductivity are assessed.

2 H-JOINTED SPSP AND H-H JOINT

H-jointed SPSP can be defined as "SPSP member with advantages in construction accuracy and economical efficiency due to welding two steel pipes with H-steel before construction" as shown in Fig. 1(b). The effects expected from application of H-jointed SPSP compared to using SPSP with traditional joints (Fig. 1(a)) are as follows; (1) H-joint is completely water-proof, (2) Two connected piles are driven simultaneously thus reducing the number of driven piles, (3) Short construction periods and reduction in operation costs are achieved when two piles are driven at the same time, and (4) H-jointed SPSP have high bending rigidity because H-steel section is welded rigidly and continuously against two steel pipes. On the hand, the H-H joint will have a number of merits over the traditional joints, they include: (1) economical efficiency by using existing H-steels, (2) high rigidity, and (3) low hydraulic conductivity of the joint part. The H-H joint is designed to alternate in series with the H-jointed SPSP as shown in Fig. 1(c) which improves

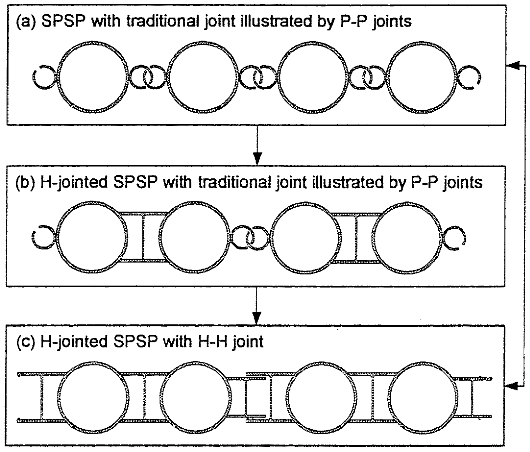


Figure 1. Stages of improvement of SPSP joints

the overall strength of the structure.

The potential of H-jointed SPSP with traditional joint (Fig. 1(b)) as vertical cutoff wall is made clear, its construction accuracy and lateral load resistance property is evaluated through field and laboratory tests. Further, tension load resistance and hydraulic conductivity of H-jointed SPSP with H-H joint (Fig. 1(c)) are verified.

3 CONSTRUCTION ACCURACY

Construction accuracy of driving SPSP as a vertical cutoff wall greatly affects their mechanical and hydraulic performance. However, there are not any specified standards for construction accuracy of SPSP in Japan. The construction accuracy of regular piles is regulated by the pile inclination angle of 1/100, and the horizontal displacement at the pile head of *D*/4 (*D*: diameter of pile) (Japan Road Association, 2002). If this regulation of regular piles was applied to the construction of SPSP; 1/100 of pile inclination means permitting a construction error of 100 mm at the bottom of an SPSP at a depth of 10 m. Typically, the diameter of a standard P-P joint pipe is 165.2 mm therefore if an error of 100 mm is permitted, the P-P joint pipes cannot interlock perfectly as shown in Fig. 1(a) and may crush altogether. Constructions of SPSP, thus, require higher driving accuracy in order to maintain verticality and achieve good joint interlocking.

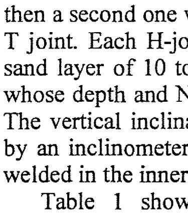
Field construction tests were conducted to check the practicality of driving H-jointed SPSP and to evaluate its construction accuracy. Three existing pile construction methods were used, they were: vibrohammer method, jetting aided vibrohammer method, and outer excavation method. Two H-jointed SPSPs were installed by each of the three methods; they were driven consecutively, the first H-jointed SPSP was driven then a second one was driven adjacent and connected to it by L-T joint. Each H-jointed SPSP driving was passed through the sand layer of 10 to 20 N-values and reached the bearing layer whose depth and N-value were 10 m and over 50, respectively. The vertical inclination of each H-jointed SPSP was measured by an inclinometer inserted through a hollow square steel box welded in the inner face of the H-steel flange.

Table 1 shows measured vertical inclinations in each construction method; X-direction represents the inclination of the pile in the direction of construction and Y-direction refers to inclination of the pile in the side perpendicular to the direction of construction as indicated in Table 1. The driving of H-jointed SPSP is more accurate compared to maximum allowed inclination of ordinary piles given as 1/100, the shape of the H-jointed SPSP is thought to be responsible for the high accuracy. It is also observed that the accuracy is dependent on the installation method. Driving two piles simultaneously controls the accuracy of construction and guarantees sound condition of the P-P joints alternating with the H-joint.

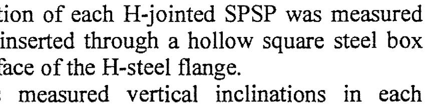
Table 1. Deformation and inclination of piles during driving

Methods	Vibrohammer		Vibrohammer with jetting		Outer excavation	
Pile No.	1st	2nd	1st	2nd	1st	2nd
Inclination						
in X-direction	-1/240	1/820	1/1150	1/1310	-1/550	1/1350
in Y-direction	-1/280	-1/250	1/380	1/310	-1/810	1/1440

(a) Soil profile and SPT results of the test site



(b) Pile deformation directions



4 MECHANICAL STABILITY OF H-JOINTED SPSP AND H-H JOINT

4.1 *Lateral load capacity of H-jointed SPSP*

Vertical cutoff wall has to be structurally stable under various external loads and have acceptable impermeability levels, H-jointed SPSP applied as a vertical cutoff wall demonstrate these two qualities.

In order to evaluate the mechanical property of H-jointed SPSP, centrifugal model tests were conducted on rectangular H-jointed SPSP foundations under lateral loading and compared with an SPSP foundation with traditional P-P joints, it is found that H-jointed SPSP exhibit higher lateral bearing capacity than SPSP with traditional joints, as shown in Fig. 2. It can be found from Fig. 2 that the H-jointed SPSP exhibits 1.5 times higher lateral capacity than the SPSP with traditional joint connections hence the effect of H-joint reinforcement on lateral load capacity (Kimura et al., 2003). This property makes application of H-jointed SPSP as vertical cutoff wall effective for reinforcement of the corner part of a double wall SPSP coastal landfill subjected to various stress concentrations. Its large lateral capacity enables size reduction of vertical cutoff wall (volume reduction of steel materials) and enables economical designs of vertical cutoff wall.

4.2 *Tension property of H-H joint*

At the corner of constructed vertical cutoff wall, the bending moments and shear forces are concentrated due to the action of many external forces peculiar to marine structures, such as an earthquakes, ocean waves, high tide water, and seismic sea waves. Consequently, the joint section of SPSP forming the corner is intensively subjected to tension stress, and results in the failure of the joints. The failure of joint section directly affects the performance of the vertical cutoff wall, and raises the risk of leachate leakages. The design of SPSP vertical cutoff wall needs to estimate quantitatively the tension resistance of the joints constituting the corner part. H-H joint is proposed to alternate with H-joints in the reinforcement of the corner part; it is formed from two H-steel sections of different sizes which interlock. At interlocked state, the joint has no tension strength therefore steel ribs welded at the interlocking surfaces of the H-H joint are proposed to provide tension strength as shown in Fig.

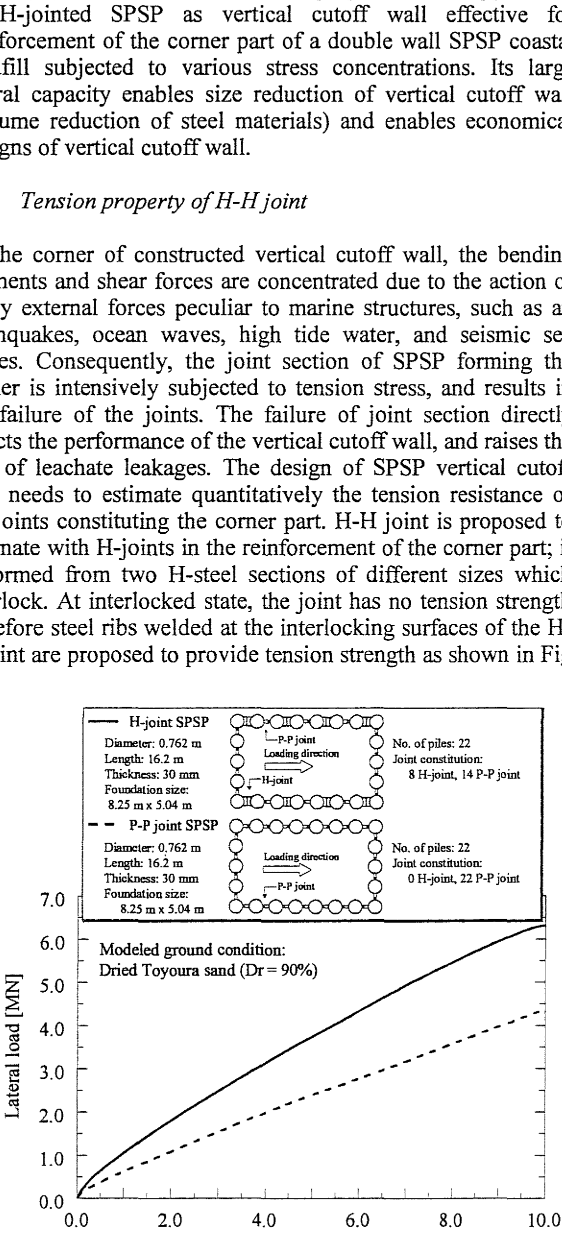


Figure 2. Lateral resistance property of H-joint and P-P joint SPSPs

3. Full-size mortar filled H-H joints with the ribs are tested in tension to evaluate their tension capacity and explain their failure mechanism. For comparison, P-P and L-T joints are also tested in tension.

Ttensile load was applied at a rate of 1mm/min until the joints underwent a displacement of 20 mm. The structure of the test specimen was such that actual in-situ conditions were reproduced, the mortar filling the joints was made in the ratio of cement 2: sand 4: water 1 equivalent to field standard mixing ratio, batching was by weight. The test specimens were tested for tension resistance after curing for 28 days, at which time the compressive strength of the filling mortar had stabilized.

Figure 3 shows the relationship between tension resistance of each of the tested joints against resulting displacements and the schematic overview of each joint type. P-P joint has low tension resistance compared to the other joints, this is because piles making the P-P joint are circular in shape (C-shaped steel); the C-shaped steel undergoes large bending under tension load. L-T joint sustains its tension resistance until failure of the mortar under compression occurs, it shows elastic behavior at small applied load to a displacement of about 3 to 4 mm beyond this it progressively weakens; this behavior may be attributed to the bending behavior displayed by this joint. In H-H (Type-1) joint, the ribs deform by bending and do not contribute much after the onset of deformation, it sustains tension load to a displacement of about 4 mm. It may be said that P-P, L-T, and H-H (Type-1) joints do not have a structural configuration that can sufficiently resist high levels of tension load. At initial loading, H-H (Type 2) joint has no tension resistance because the mortar filling cannot carry tension load, however, when the steel ribs touch it becomes stiff because the loading direction is parallel to the flanges of the H-steel which result in full mobilization of axial tension strength. Its ribs are short therefore do not deform by bending. Mortar in H-H joint (Type-2) does not contribute to tension strength of this joint, it is thus the strongest. H-H joint can resist tension under both conditions of Type-1 and Type-2. Several application combinations of the ribs are proposed as follows; (1) Both ribs may be combined so that the two types of ribs are used at the same time. At initial loading conditions H-H (Type-1) joint takes tensile load which is then taken up by H-H (Type 2) joint at higher load levels. However, because of cost implications it is sugested that this

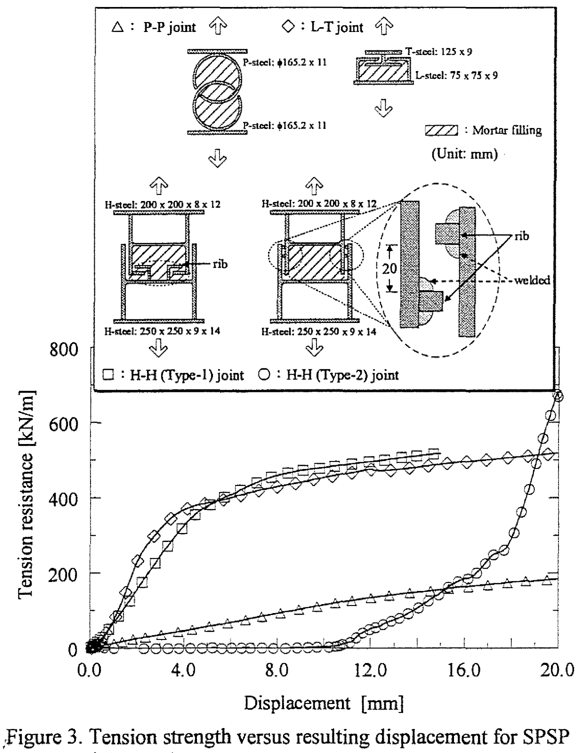


Figure 3. Tension strength versus resulting displacement for SPSP joint sections

hybrid type need not be used on all sections of the vertical cutoff wall structure. From prior analysis done before construction execution, sections of the structure which are likely to experience severe tension loads shall be identified. (2) Mortar filled H-H (Type-1) joint may be used in the upper part of H-H joint SPSP segment upto several meters penetration depth, below this depth the H-H joint SPSP segment shall have H-H (Type-2) joint to the bearing layer. Depending on the significance of the structure, H-H (Type-1) joint may be adapted or H-H joint which has no rib at all is used.

For increased overall rigidity of SPSP vertical cutoff wall it will be necessary to use a footing over the heads of H-H joint SPSP as a means of further reinforcing the structure and securing the H-H joint in place.

5 HYDRAULIC CONDUCTIVITY OF H-JOINTED SPSP WITH H-H JOINT

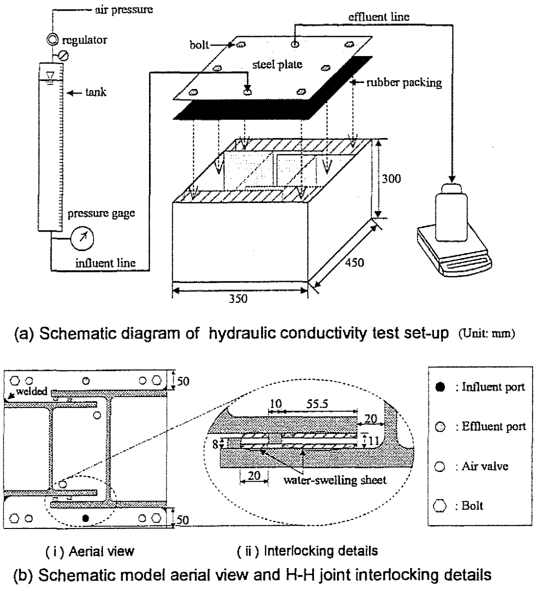
It is of critical concern to decrease the permeability of SPSP joints to meet technical standard requirements for application as a vertical cutoff wall; in H-jointed SPSP with H-H joint, the H-joint is completely waterproof, however, with H-H joint is not waterproof at interlocked state because a gap of 8 to 11 mm is left between the interlocking flanges therefore a waterproof treatment must be conducted to seal the gap. The treatment of H-H joint is executed by coating the gaps with a water-swelling sheet before its installation; use of mortar filling is not required.. Among the problems of traditional joints in respect to waterproofing capacity include: (1) the joint so grouted has low rigidity, (2) failure of the joint structure during the construction may occur, (3) the pollution of a nearby sea area with the leakage of mortar, (4) it is difficult to apply waterproof treatment to the curved surfaces of the traditional joints, and (5) it is also difficult to control and ensure the quality of waterproof treatment. These problems are overcome by development of high performance H-jointed SPSP with H-H joint systems.

Hydraulic conductivity test for H-H joint section was carried out using permeability test equipment and test specimen, as shown in Fig. 4. The water-swelling sheet is coated to the interlocking surfaces of each H-steel (Fig. 4(b)). The thickness of coated water-swelling sheet affects its volume of swelling and pressure of swelling, and the level of hydraulic conductivity of H-H joint is consequentially influenced by its thickness. In the hydraulic conductivity test, the hydraulic conductivity of H-H joint is evaluated when it is coated with water-swelling sheets of three different thicknesses i.e. 1, 2, and 3 mm sheets. The influent pressure was gradually increased from 0.02 to 0.5 MPa for the test specimen coated with each of the three water-swelling sheet thicknesses. The retention time of the influent pressure was kept for 6 hours in each case, and flow rate of influent and effluent was measured, while unit time water balance of influent and effluent was confirmed.

Generally, the hydraulic conductivity of SPSP is evaluated using an equivalent hydraulic conductivity (k_e) which is converted from that of SPSP to k_e equivalent to a uniform permeable soil layer of 50 cm thickness (Kamon and Inui, 2003). As shown in Fig. 5, it is assumed that the flow-path (B) for SPSP includes the two H-jointed piles, the H-joint, and part of the H-H joint.

The water-swelling paint swells when it comes in contact with water; it is a solid with fluidity blending of water-absorbing polymer into synthetic-resin elastomer as a base material. Water extracted from dried coating film of the water-swelling paint has been tested and found to satisfy standards for water-purity based on food hygiene law in Japan. The water-swelling paint used in the experiment begins to swell after it comes in contact with water, and achieving a hydraulic conductivity of 1.42 x 10^{-9} cm/s.

Figure 6 shows equivalent hydraulic conductivity k_e for H-jointed SPSP with H-H joint sealed with water-swelling sheets



(a) Schematic diagram of hydraulic conductivity test set-up (Unit: mm)

(b) Schematic model aerial view and H-H joint interlocking details

Figure 4. Hydraulic conductivity test layout, model aerial view and details of H-H joint interlock

of thickness 1, 2, and 3 mm against water pressure; also shown are k_e for P-T joints sealed by mortar and rubber (Oki et al., 2003). It is observed that k_e for H-H joint depends on thickness of the sealant applied and the level of water pressure. The water-swelling sheets with thickness of 2 mm and above meet specified hydraulic conductivity of $k_e \leq 10^{-6}$ cm/s (Kamon and Jang, 2001) for vertical cutoff walls up to water pressures of 0.5 MPa. In coastal landfills, maximum water level difference between the contained water and the outer sea level must not exceed 2 m; this level is controlled during heavy rains, water tide variations, and high water waves. However, reports indicate that some landfills have been filled to 5 m way beyond the specified limit of 2 m water level difference. Therefore, it is important to evaluate k_e of H-jointed SPSP with H-H joints for application as a vertical cutoff wall based on the 5 m rather than the specified 2 m water level difference. The k_e for H-H joints coated with 1 and 2 mm sheets is very low in the order of 10^{-8} cm/s at a water pressure of 0.05 MPa; k_e for H-H joint coated with 3 mm sheets was too small and could not be measured, since there was not effluent flow collected in the 6 hour test duration, k_e can be said to be below 1 x 10^{-9} cm/s. The authors propose use of $k_e = 10^{-8}$ cm/s in design of H-jointed SPSP with H-H joint sealed with this water-swelling sheet.

When compared with findings of Oki et al. (2003), at 0.05 MPa the H-H joint has k_e of 2-order difference compared with the P-T joint sealed with mortar. The P-T joint sealed with mortar and rubber membrane is found to have $k_e = 10^{-8}$ cm/s like was the case with H-H joint, however, this value is based on laboratory findings in which application of mortar and the rubber membrane can easily be controlled; the case may not necessarily be true in actual construction practice because the waterproof treatment of P-T joint is done after construction and SPSP with P-T joint have low installation accuracy. Based on the construction advantages of the H-jointed SPSP and backed by the measured low hydraulic conductivity of H-jointed SPSP with H-H joint, the use of H-jointed SPSP with H-H joint sealed by water-swelling sheet is highly recommended as a vertical cutoff wall in coastal landfills.

6 CONCLUSIONS

The following conclusions were drawn from this study:

(1) H-jointed SPSP has high rigidity, two connected piles can be installed simultaneously; it can control the accuracy of construction and guarantee sound condition of the P-P joints during driving.

(2) H-jointed SPSP exhibits 1.5 times higher lateral bearing capacity than SPSP with traditional joint connections. This shows that H-jointed SPSP have superior mechanical stability and clarifies the effect of H-joint reinforcement on lateral load capacity of SPSP.

(3) With the use of steel ribs, H-H joint demonstrates larger tension resistance than P-P and L-T joint which deform by moment effects.

(4) Hydraulic conductivity of 10^{-8} cm/s is proposed for use in design of H-H joints sealed with this water-swelling hydraulic sealant sheet in applying as a hydraulic cutoff wall in coastal landfills.

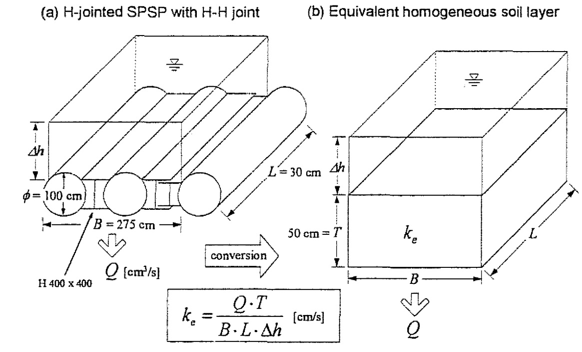


Figure 5. Conversion of the size of H-jointed SPSP with H-H joints into an equivalent homogeneous soil layer

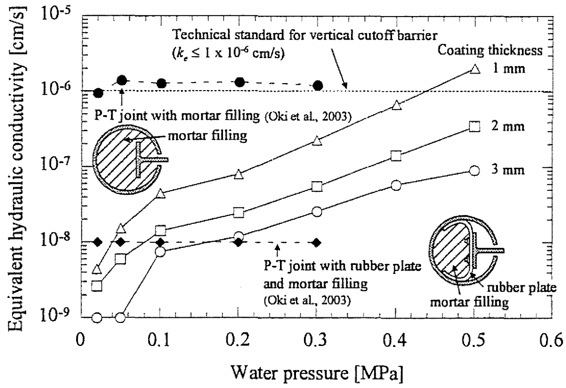


Figure 6. Equivalent hydraulic conductivity versus resisted water pressure

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