SOILS AND FOUNDATIONS Vol. 51, No. 6, 1019–1035, Dec. 2011
Japanese Geotechnical Society

WATER CUT-OFF PERFORMANCE OF H-JOINTED STEEL PIPE SHEET PILES WITH H-H JOINTS ATTACHING WATER-SWELLING MATERIALS

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ABSTRACT

In this research, under various conditions, we evaluate the water cut-off performance of H-jointed steel pipe sheet piles (SPSPs) with the H-H joints attaching water-swelling materials which are components of SPSPs for water cut-off in a coastal waste landfill site. Specifically, we research the water cut-off performance when these H-H joints have foreign particles, when they are in a wet-dry cyclic condition, and when the water-swelling material has deteriorated. As a result of this research, it has been found that in any of the above cases, H-jointed SPSPs with H-H joints attaching water-swelling materials are capable of providing water cut-off performance, and meet seepage control work standards as long as they are under less than certain pressure levels to be considered in coastal waste landfill sites. Also, it has been proved that the above conditions do not affect the water cut-off performance of H-jointed SPSPs with H-H joints attaching water-swelling materials.

Key words: cutoff wall, H-jointed steel pipe sheet pile with H-H joint, hydraulic conductivity, joint, permeability test, steel pipe sheet pile, waste landfill site, water-swelling material (**IGC**: H2/H7)

INTRODUCTION

In the past in Japan, waste landfill sites were relatively small, and built in the river-head areas of mountain valleys (referred to below as ‘‘inland waste landfill sites’’). These days, however, there has been an increasing tendency to construct larger coastal waste landfill sites in urban bay areas to preserve water resources and to protect groundwater from pollution by leachate from the waste landfill sites (WVERC, 2002; TLSTRAJ, 2004; Inazumi et al., 2009).

In a coastal waste landfill site, a coastal revetment is built to secure an area to landfill waste, after coordinating with port conservation (*see* Fig. 1). This coastal revetment has to protect the landfill area from various external forces specific to coastal areas, such as earthquakes, ocean waves, high tide water and tsunamis, and also be constructed in such a way that seepage is controlled to prevent the leachate from the waste landfill site from leaking into the sea (TLSTRAJ, 2004; WVERC, 2002; Inazumi et al., 2009). In recent years, SPSPs with joints, which can be installed in deep water, have been widely used in coastal waste landfill sites as coastal revetments since they are both easy to install and economical. In the following text, side seepage control work (coastal revetments) consisting of steel pipe sheet piles (SPSPs) is referred to as ‘‘SPSPs cutoff walls’’.

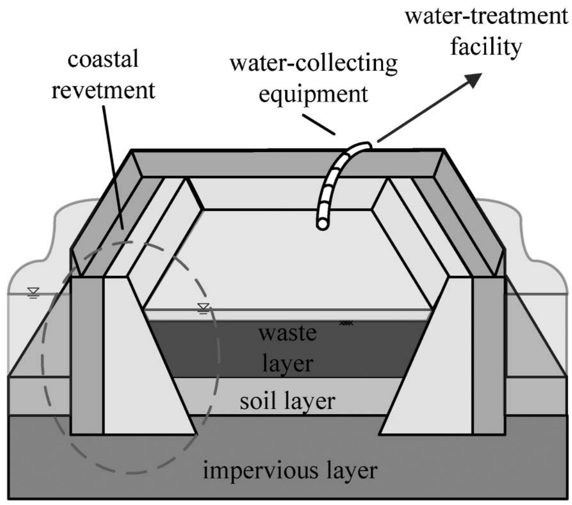

Fig. 1. Coastal revetments installed in a coastal waste landfill site

Since 1960, when SPSPs were used in sheet pile quay walls for the first time, various approaches have been attempted for the joints, which are significant because they

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The manuscript for this paper was received for review on January 24, 2011; approved on June 8, 2011.
Written discussions on this paper should be submitted before July 1, 2012 to the Japanese Geotechnical Society, 4-38-2, Sengoku, Bunkyo-ku, Tokyo 112-0011, Japan. Upon request the closing date may be extended one month.

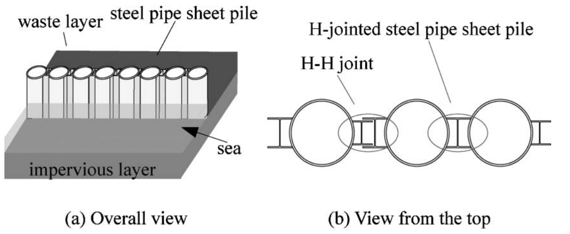


Fig. 2. H-jointed SPSPs with H-H joints

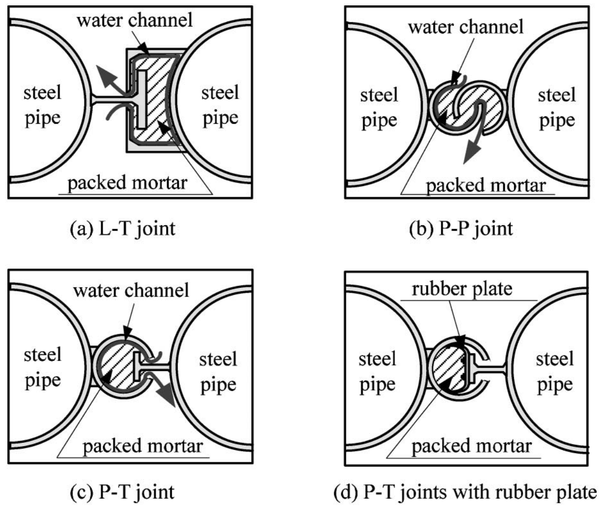


Fig. 3. L-T, P-P and P-T joints of SPSPs, and P-T joints with rubber plate

affect the leakage of water-soluble hazardous substances in waste landfill sites. The H-jointed SPSPs with H-H joints (*see* Fig. 2) developed in recent years (Kimura and Inazumi, 2007; Kimura et al., 2007; Inazumi et al., 2008; Inazumi and Kimura, 2009a, 2009b) have demonstrated superior physical stability and water cut-off performance compared to traditional joints. As mentioned above, SPSPs cutoff walls in coastal waste landfill sites are influenced by the elements specific to coastal areas. However, whether such influence is critical or not depends on the installation environment of the SPSPs cutoff wall. Also, the SPSPs cutoff walls must be capable of maintaining their water cut-off performance for periods as long as 50 or 100 years, until the coastal waste landfill site is decommissioned. However, the water cut-off performance of H-H joints has been evaluated mainly through reviewing various influences without attention paid to the installation environment, and the influences specific to the conditions of each installation have not yet been verified. In addition, the existing research has evaluated the water cut-off performance of H-H joints only at the start of their use and has not quantitatively explained the water cut-off performance after the deterioration associated with the usage of water-swelling material has occurred.

Therefore, in this research we examine the water cut-off performance of H-H joints when they are influenced by various elements specific to the installation environment and when considering the deterioration of the water-swelling material used as the water cut-off material.

PERFORMANCE OF STEEL PIPE SHEET PILES AND JOINTS

Water Cut-off Treatment of Traditional Joints

Generally, in coastal waste landfill sites, SPSPs materials with various joints such as L-T, P-P and P-T joints interlock and are installed sequentially as SPSPs cutoff walls (*see* Fig. 3(a), (b), (c)). However, the interlocked joints form spaces for water to pass inside and it is very likely that leachate from the landfill site passes through these joints. Therefore, in building SPSPs cutoff walls, measures to improve the water cut-off performance of the joints (water cut-off treatments) have to be implemented.

For water cut-off treatment for L-T, P-P and P-T joints, it is common to fill low permeable sacking mortar or asphalt into the joints after installing SPSPs to reduce hydraulic conductivity in the joints. However, in the water cut-off treatment, a water channel is generated along the contact interface between the filled sacking mortar and the joint steel, when the mortar is filled unevenly in the recess of a joint (*see* Fig. 3(a), (b), (c)) (Inazumi and Kimura, 2009a, 2009b). Also, for installing SPSPs with the existing type of joints, competition and push and pull occur while tilting or rotating the SPSPs, and healthy joint forms cannot be kept towards the depth direction (Inazumi et al., 2008). Therefore, it is difficult for such inappropriately interlocked joints to perform water cut-off treatment effectively after installation. However, currently, there are only a few reviews or development of technologies of water cut-off treatment by existing joint types, regarding the installation capability of SPSPs.

As a crafting technique of water cut-off treatment using the existing joint structure, an improved P-T joint was developed where sacking mortar with leakage prevention rubber sheet is attached and steel pipes with slits are used (*see* Fig. 3(d)) (Oki et al., 2003). Further, an existing P-T joint filled with only sacking mortar was compared to the improved P-T joint, and it was concluded that the equivalent hydraulic conductivity (k_e) of the existing P-T joint is of the order of $k_e = 1 \times 10^{-8}$ m/s while that of the improved P-T joint is less than $k_e = 1 \times 10^{-10}$ m/s order, and they have excellent water cut-off ability (Oki et al., 2003). However, it is harder to precisely install SPSPs with P-T joints equipped with leakage prevention rubber sheet and the cost associated with water cut-off can only increase. Also, when evaluating the water cut-off performance of SPSPs connected via joints, it is usual to regard the joints and steel pipes as one set and use an equivalent hydraulic conductivity, k_e, assuming the SPSPs structure to be a flat impervious layer (water cut-off layer) with an even thickness (d) of 500 mm (*see* Fig. 4) (Kamon and Jang, 2001; Kamon et al., 2001).

In addition, when considering maintenance and repair, it is difficult to find any water channels because the mor-

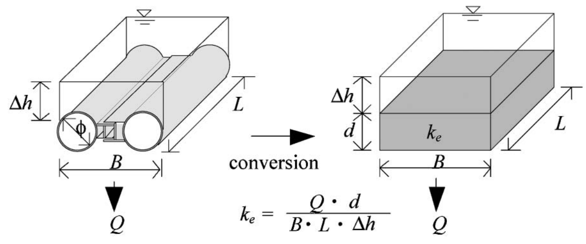


Fig. 4. Image of equivalent hydraulic conductivity (k_e)

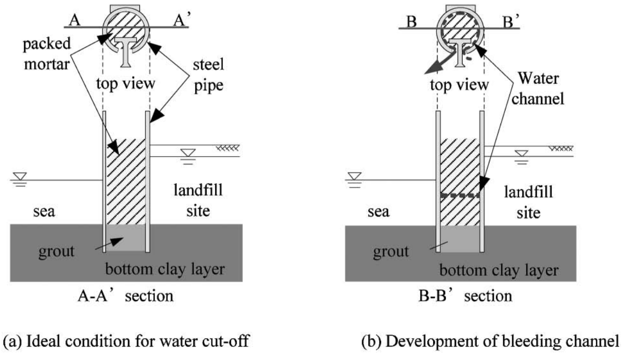


Fig. 5. Issues of traditional joints regarding maintenance and repair

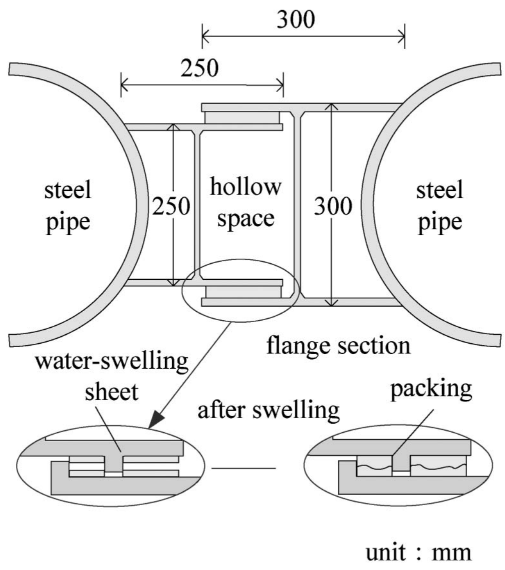


Fig. 6. H-H joints with water cut-off treatment using water-swelling material

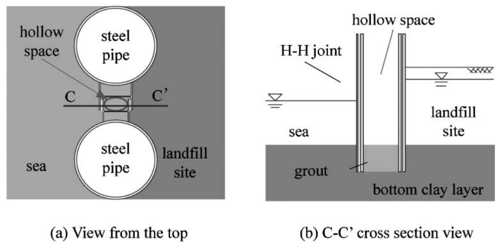


Fig. 7. Hollow space inside the H-H joints

tar, etc. is filled towards the depth direction of the joints in cases where the water channel is generated due to inappropriate installation techniques (*see* Fig. 5). Also, even if we can identify the site using sensors, etc., it is likely that the repair operation for the water channel is quite challenging. When considering long-term usage over period of 50 or 100 years, the maintenance and repair of the P-P, P-T, L-T and improved P-T joint, if the water cut-off performance has deteriorated, would imply a lot of problems.

Water Cut-off Performance of the H-jointed SPSPs with H-H Joints Attaching Water-swelling Materials

To solve the defects inherent in SPSPs cutoff walls with traditional joints such as P-P, P-T, L-T and improved P-T joints, innovative SPSPs materials called ''H-H joint'' and ''H-jointed steel pipe sheet piles'' were developed in recent years (*see* Fig. 2) (Kimura and Inazumi, 2007; Kimura et al., 2007; Inazumi et al., 2008; Inazumi and Kimura, 2009a, 2009b).

The ''H-H joint'' forms a joint by interlocking two different types of H form steels, and consists of two independent flanges and a inside the joint. On the other hand, ''H-jointed SPSPs'' consist of two steel pipes connected via H-steel. Because the welding of the H-steel and steel pipe is done before installation, no problems should occur during welding.

Perfect water cut-off performance is achieved by the H-jointed SPSPs with H-H joints because H-steels and steel pipes are rigidly connected in the H-jointed SPSPs. In other words, among components of the H-jointed SPSPs with H-H joints, only H-H joints require water cut-off treatment. Because the H-jointed SPSPs with H-H joints used as SPSPs cutoff walls halves the number of joints, the water cut-off performance is dramatically improved compared to SPSPs cutoff walls used in the past.

Meanwhile, water-swelling material coated and attached onto the contact surface of the flange where slits with 8 to 11 mm width are formed on each H-steel assures the water cut-off performance (*see* Fig. 6) (Inazumi and Kimura, 2009a, 2009b). Here, the water-swelling material attached to the flange is an elastic material mainly consisting of synthetic resin elastomer and mixed with super-absorbent polymer, fillings, solvent, etc., which meets environmental standards. The water extracted from a dried film of water-swelling material fulfills the Food Sanitation Law Standards and is not harmful to the environment. At present, the composition of frequently used water-swelling materials is such that when it is soaked in plain water or sea water for 24 hours, it swells up to 15–30 times and 5–7 times, respectively, in terms of weight ratio (Inazumi et al., 2010). Also, inside the H-H joints where the water cut-off treatment is implemented by the water-swelling material is forced with approximately 200×200 mm is formed (*see* Figs. 6 and 7). Therefore, because it is not necessary to fill the entire space of the H-H joints with low permeable material such as sacking mortar, space can be used for other applications such as monitor-

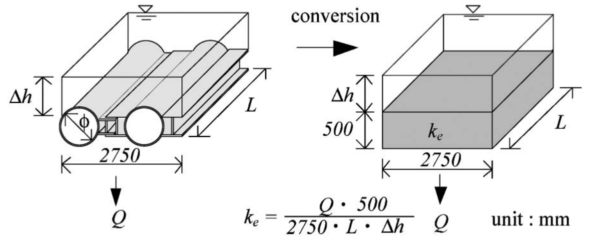


Fig. 8. Image of equivalent hydraulic conductivity (k_e) of H-jointed SPSPs with H-H joints

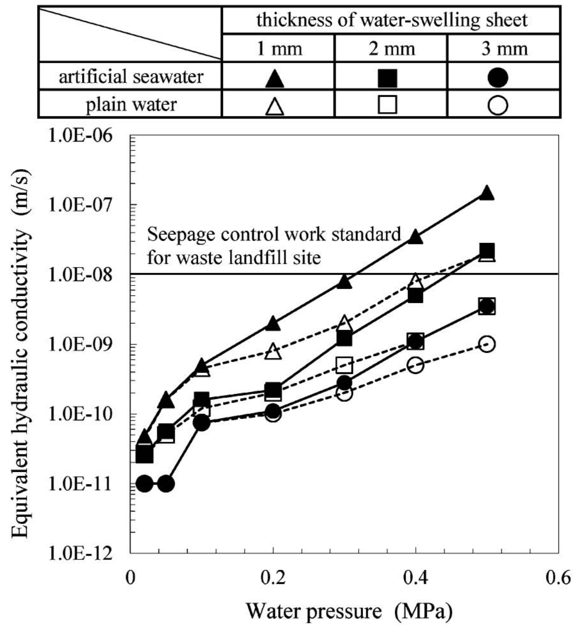


Fig. 9. Relationship between water pressure and equivalent hydraulic conductivity

ing. Previous research has demonstrated from existing observations that cleaning earth and sand from the inside the H-H joints can be implemented reliably and completely (Inazumi and Kimura, 2009a, 2009b).

Regarding the water cut-off performance of the H-jointed SPSPs with H-H joints attaching water-swelling materials, permeability tests are implemented under various conditions (Kimura et al., 2007; Inazumi et al., 2008; Inazumi and Kimura, 2009a, 2009b). For example, as long as the actual water pressure is less than 0.05 MPa (water head difference: 5 m) in a coastal waste landfill site, the H-jointed SPSPs with H-H joints attaching water-swelling materials show the same water cut-off performance with both artificial sea water and plain water. Also, when the thickness of water-swelling material attached is any of 1, 2, or 3 mm, it meets the equivalent hydraulic conductivity: $k_e \leq 1 \times 10^{-8}$ m/s, which is the seepage control work standard for waste landfill sites (*see* Figs. 8 and 9) (Inazumi and Kimura, 2009a, 2009b). In addition, deterioration behavior (referred to as ''deterioration'' below) of the water-swelling material attached to the flange of an H-H joint is also reviewed and researched using the strength of the swelling membrane (Inazumi et al., 2010). Figure 10 shows the result of strength tests of the swelling membrane implemented by Inazumi et al. (2010) who reported that the strength of the swelling membrane applied to H-H joint is reduced from about 930 to about 140 kPa over the course of a year and after that it continues to show a certain constant value. The strength of swelling material was defined as the strength required (by the penetration elastic tool with a 3 mm diameter) for penetration and breaking of the water-swelling material (Inazumi et al., 2010). It is believed that this effect is caused because a superabsorbent polymer included in the water-swelling material continues to elute for a year from the beginning of the curing and after that year, the elution is complete. In other words, when the H-H joint is installed in an environment where the water temperature is 20°C, most of the deterioration of water-swelling material occurs in the first year, after which the deterioration almost stops.

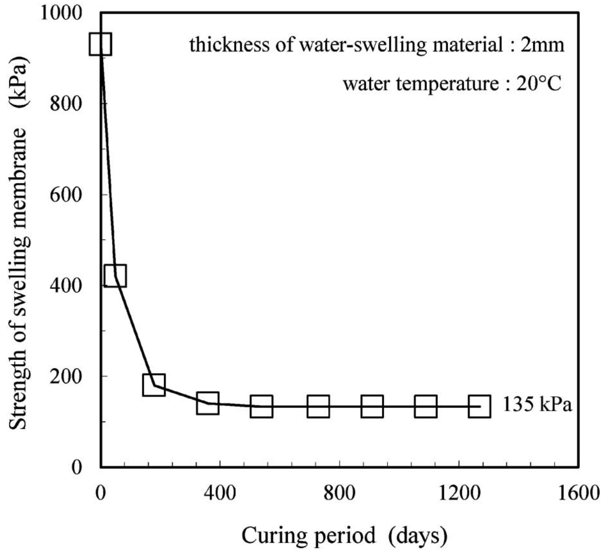


Fig. 10. Deterioration of strength of water-swelling material (swelling membrane) over time

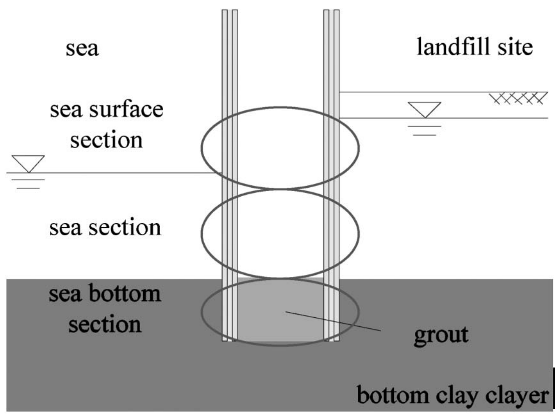


Fig. 11. Classification according to installation environment of SPSPs cutoff walls

However, the SPSPs cutoff walls in coastal waste landfill sites must maintain their water cut-off performance for 50 or 100 years from installation to abolishment regardless of their installation environment, whether on the sea surface, under the sea or on the sea bed (*see* Fig. 11). It means that superior water cut-off performance has to be maintained not only under the influences specific to the installation environment and the deterioration of the water cut-off material due to normal usage, but they also must be able to handle unexpected phenomena such as earthquakes, etc. As such, it is important to evaluate the water cut-off performance of the H-jointed SPSPs with H-H joints attaching water-swelling materials under various conditions.

Therefore, this research discusses the water cut-off performance of the H-jointed SPSPs with H-H joints attaching water-swelling materials under five conditions of influence specific to the installation environment; damage of water-swelling material, penetration of foreign substances into H-H joints, Alternate Wetting and Drying (AWD) by tides, deterioration of water-swelling material due to normal usage, and repeated shear deformation by external forces such as earthquakes.

THE WATER CUT-OFF PERFORMANCE WITHOUT WATER-SWELLING MATERIAL

Summary

At the installation of SPSPs cutoff walls in coastal waste landfill sites, the physical stability of SPSPs is ensured through the vibration impact method using a vibro-hammer, which inserts the SPSPs into the sea bottom ground. Here, the water cut-off performance of H-jointed SPSPs with H-H joints is assured by swelling of the water-swelling material attached and coated onto the H-H joints. However, because the water-swelling material is attached and coated onto the H-H joints before the installation of the SPSPs, it is likely that the water-swelling material attached and coated onto H-H joints will be damaged at the installation of SPSPs, particularly when they are installed in the sea bottom ground. Considering this, when using the H-jointed SPSPs with H-H joints as SPSPs cutoff walls, it is important to maintain their superior water cut-off performance even when the water-swelling material is damaged.

Therefore, this research discusses the water cut-off performance of the H-jointed SPSPs with H-H joints attaching water-swelling materials when the water-swelling material is damaged, which can happen during the installation of SPSPs.

Test Method

In this research, the permeability test using the steel H-H joint model is implemented to evaluate the water cut-off performance when the water-swelling material is damaged.

Figures 12 and 13 show the details of the permeability test method outlined in this section and the steel H-H joint model used in the test. The damage patterns discussed in this research are from a total of 7 cases, with the the damage rate and the contact surface area as the

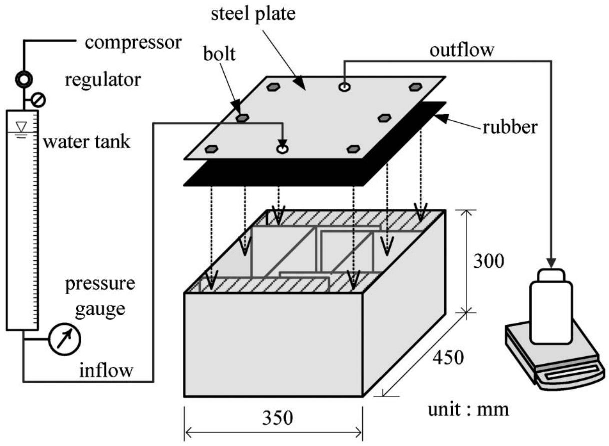


Fig. 12. Permeability test using steel H-H joint model to evaluate water cut-off performance when water-swelling material is damaged

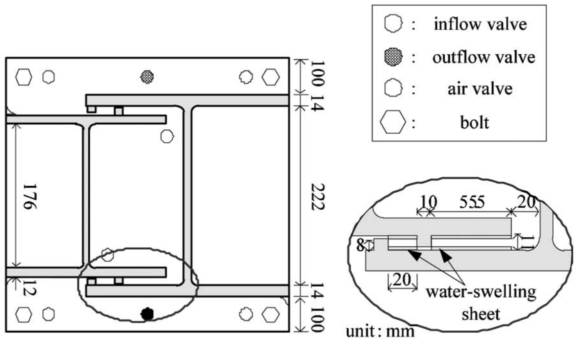


Fig. 13. Details of steel H-H joint model

Table 1. Assumption of damage patterns

Case	Damage rate (%)	(a) both sides unit : mm	(a) one side unit : mm
Case-1	0	20 10 55.5 20 11 8	
Case-2	26.5	20 10 55.5	
Case-3	50	37.8	20 10 55.5
Case-4	63.25		55.5
Case-5	75	6.5	55.5

parameters (*see* Table 1). The damage rate is defined as the amount of loss of water-swelling material in Case 1. The permeability test method is as follows:

(1) Attach the water-swelling sheet (water-swelling material) to the contact surface of the H-H joints.
(2) Completely seal the test specimen using the steel plate and leakage prevention rubber sheet.

(3) Fill the inflow water tank, the inside of the H-H joints and the outflow water tank with plain water.
(4) Leave for 24 hours at a constant temperature.
(5) Apply predefined water pressure for 6 hours and check the balance of inflow and outflow water volume per hour, and also measure the inflow and outflow current volume.
(6) Raise the inflow water pressure from 0.02 to 0.4 MPa in stages.
(7) Repeat steps (5) and (6).

The Impact by the H-jointed SPSPs with H-H Joints without the Water-swelling Material on the Water Cut-off Performance

Figure 14 shows the relationship between the equivalent hydraulic conductivity of the H-jointed SPSPs with H-H joints attaching water-swelling materials and the applied water pressure in each case.

In each case, as long as the water head difference is 5 m (the applied water pressure is 0.05 MPa), which should be assumed in a coastal waste landfill site, the H-jointed SPSPs with H-H joints attaching water-swelling materials meet the seepage control work standard (equivalent hydraulic conductivity: $k_e \leq 1.0 \times 10^{-8}$ m/s). More specifically, when the water head difference is 5 m (applied water pressure is 0.05 MPa.), the highest equivalent hydraulic conductivity is found in Case-5(b), where the water-swelling material is attached and coated onto one surface inside the flange of H-H joints with the damage rate at 75%. However, since the equivalent hydraulic conductivity is still $k_e \leq 5.1 \times 10^{-10}$ m/s, it can be said that it provides superior water cut-off performance. Also, in the case where the water-swelling material is attached and coated on to both sides of the contact surface inside the flange of the H-H joints, it provides superior water cut-off performance compared to the case where it's applied to only one side of the contact surface. For example, when comparing Case-3(a) with Case-3(b) at a water level difference of 5 m (the applied water pressure is 0.05 MPa.), where the damage rate is 50%, (a) where the water-swelling material is applied to both sides of the contact surface shows $k_e \leq 9.1 \times 10^{-11}$ m/s as the equivalent hydraulic conductivity, while (b) where the water-swelling material is applied to one side of the contact surface shows $k_e \leq 2.3 \times 10^{-11}$ m/s. That means the former has superior water cut-off capability. Further, this trend becomes more significant as the water level difference (applied water pressure) is larger and the difference between Case-5(a) and Case-5(b) is more than 1 order of magnitude. This can be presumed to have arisen from the swelling pressure of the water-swelling material after swelling inside the H-H joints (Inazumi et al., 2011). When the water-swelling material exists on only one side of the contact surface inside the flange of the H-H joints, the material needs to swell by 9 mm in height (the flange interval is 11 mm, the original thickness of the material is 2 mm) to fill the inside the flange of the H-H joints. Meanwhile, when the water-swelling material exists on both sides of the contact surface inside the flange of the H-H joints, the material needs to swell by 7 mm of height (the flange interval is 11 mm, the total thickness of the materials is 4 mm) to fill the inside the flange of the H-H joints so it can gain higher swelling pressure than the case when the material is on only one side of the contact surface (*see* Fig. 15).

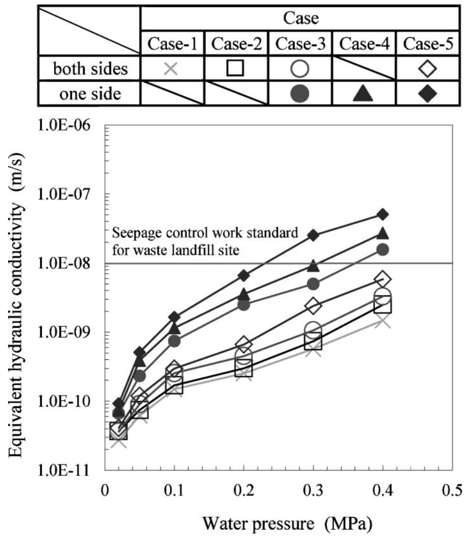


Fig. 14. Relationship between equivalent hydraulic conductivity and applied water pressure in case of loss of water-swelling material

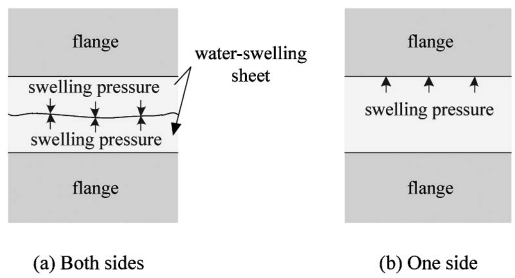


Fig. 15. Swelling pressure generated at contact surface inside the flange of H-H joints

THE WATER CUT-OFF PERFORMANCE WHEN A FOREIGN SUBSTANCE HAS PENETRATED

Summary

At the installation of SPSPs cutoff walls in coastal waste landfill sites, the physical stability of SPSPs is ensured through the vibration impact method using a vibro hammer, which inserts the SPSPs into the sea bottom ground. Here, if the H-jointed SPSPs with H-H joints with water-swelling materials attached are used in SPSPs cutoff walls, they will provide superior water cut-off performance under any conditions of installation. When considering the H-jointed SPSPs with H-H joints with water-swelling materials with installed in the sea bottom ground, the bottom ground is stirred due to the vibration impact method. That is, stirred soil particles can exist in the flanges inside the H-H joints. It has been shown in previous studies that earth and sand are always completely cleaned from the of H-H joints (Inazumi and Kimura, 2009a). However, it is physically difficult to thoroughly clean the flange part of the H-H joints since the flange spacing is only about 10 mm and the water-swelling material is in the way. Therefore, it is likely there are stirred soil particles inside the flange. Also, apart from the soil, it is likely there are other substances such as plastic floating at sea level, and these may also penetrate into the flange. It is important to assure superior water cut-off performance even when foreign substances penetrate into the flange because the H-jointed SPSPs with H-H joints attaching water-swelling materials are required to maintain excellent water cut-off performance in any installation environment.

Therefore, this chapter discusses the water cut-off performance of the H-jointed SPSPs with H-H joints with water-swelling materials attached under conditions where foreign substances such as soil penetrate, which can happen in various installation environments.

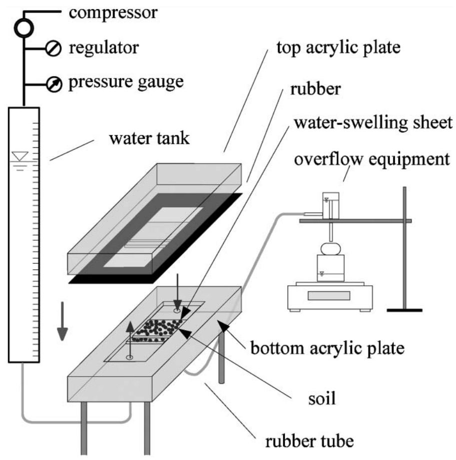


Fig. 16. Permeability test using acrylic H-H joint flange model to evaluate water cut-off performance when foreign substances penetrate into flange of H-H joints

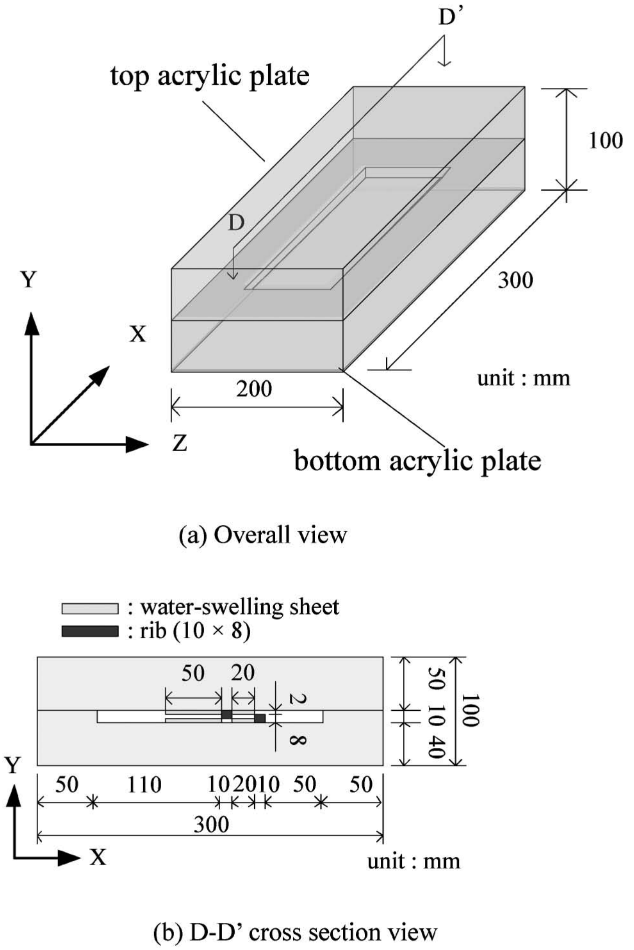


Fig. 17. Details of acrylic H-H joint flange model

Test Method

In this research, the permeability test and swelling visualization test are implemented using an acrylic H-H flange model to evaluate the water cut-off performance when foreign substances penetrate into the flange of the H-H joints.

Figures 16 and 17 show the details of the permeability test method described in this section and the acrylic H-H flange model used in the permeability test. The permeability test method is as follows:

(1) Attach water-swelling sheets (water-swelling materials) of predefined thickness to the top and bottom acrylic plates.
(2) Apply soil particles with predefined filling rate on to the surface of the water-swelling sheet attached to the bottom acrylic plate.
(3) Bolt the top and bottom acrylic plates together (Spacing: 10 mm) to make a permeability test specimen.
(4) Use the water tank to fill the permeability test specimen and leave it for 24 hours (swell the attached water-swelling sheets).
(5) Adjust the water head difference to be 5 m and implement the permeability test.
(6) Measure the leakage after an hour to calculate the hydraulic conductivity.

In this test, the measured time of leakage is set to one hour. This allows the use of the equivalent hydraulic conductivity $k_e \leq 1.0 \times 10^{-11}$ m/s in case the cumulative leakage cannot be checked after an hour. Also, the filling rate is the volume of soil penetration against the volume of the space created between the top and bottom water-swelling sheets (*see* Fig. 18).

In addition, the test specimen for the swelling visualization test is shown in Fig. 19 and the test steps are as follows:

(1) Install water-swelling sheets of predefined thickness (50×100 mm, 20×100 mm) on the top and bottom acrylic plates.
(2) Apply soil particles with predefined filling rate onto the surface of the water-swelling sheet attached to the bottom acrylic plate.
(3) Bolt the top and bottom acrylic plates together to make a visualization test specimen.
(4) Use the water tank to fill the visualization test specimen and leave it for 24 hours (swell the attached

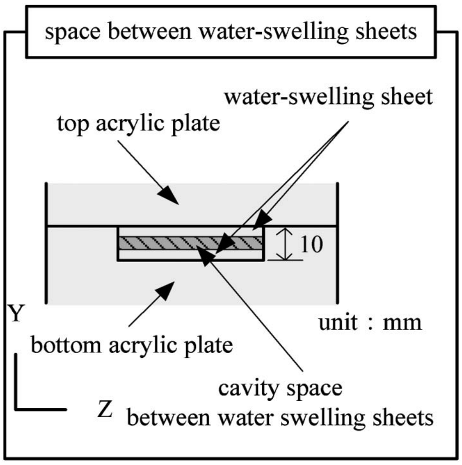


Fig. 18. Space between water-swelling materials

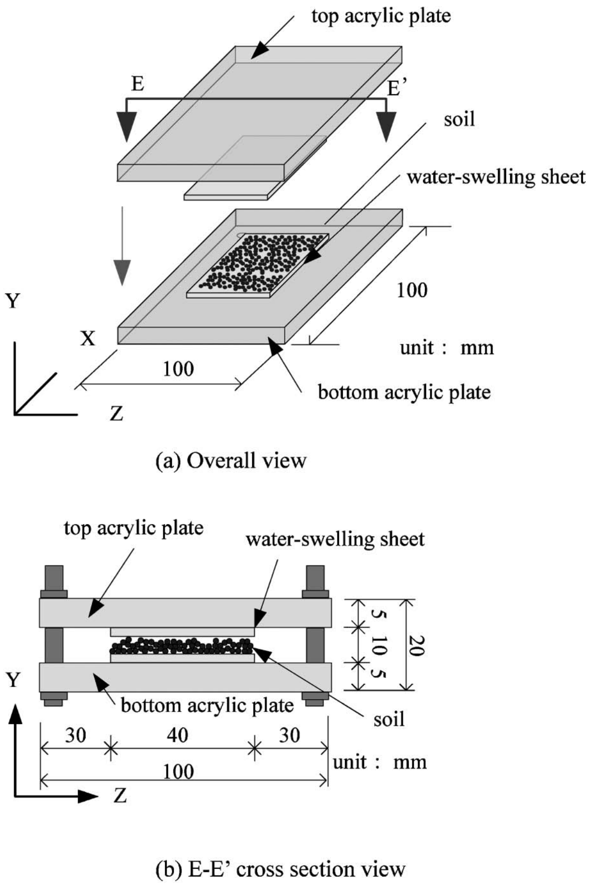


Fig. 19. Specimen for visual check of contact surface after swelling test

water-swelling sheets).

(5) After checking the swelling of the water-swelling sheets, cut off the sheets to photograph the cutting surface.

The Impact from the H-jointed SPSPs with H-H Joints Attaching Water-swelling Materials on the Water Cut-off Performance when Foreign Substances Penetrate

This section discusses the water cut-off performance of

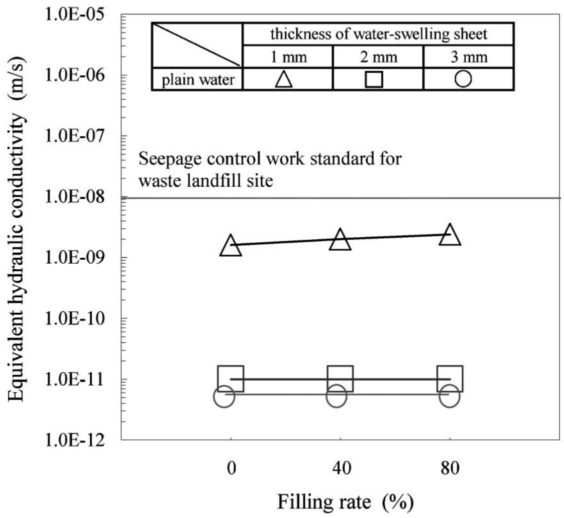


Fig. 20. Relationship between equivalent hydraulic conductivity and filling rate of foreign substances (soil particles)

the H-jointed SPSPs with H-H joints with water-swelling materials attached when foreign substances penetrate into the flange of the H-H joints and also the swelling behavior on the contact surface of the water-swelling material.

Figure 20 shows the result of the permeability test where the thickness of the water-swelling sheet changes from 1 to 2 and 3 mm and the filling rate changes from 0% to 40% and 80%, with a water head difference of 5 m. Figure 20 shows that if the filling rate is 0% and the thickness of the water-swelling sheet is 2 or 3 mm, there was no leakage even after an hour from the beginning of the permeability test. Therefore, when the thickness of the water-swelling material attached to the H-H joints is 2 or 3 mm and there is no foreign substance in the flange of H-H joints, the H-jointed SPSPs with H-H joints with water-swelling materials attached provides better water cut-off performance than the equivalent hydraulic conductivity, $k_e = 1.0 \times 10^{-11}$ m/s. Also, if the thickness of the water-swelling sheet is 1 mm and the filling rate is 0%, it has been proven that the H-jointed SPSPs with H-H joints with water-swelling materials attached have the equivalent hydraulic conductivity of $k_e = 1.6 \times 10^{-9}$ m/s. Moreover, if the filling rate is 80% and the thickness of the water-swelling sheet is 2 or 3 mm, there is no leakage even after an hour from the beginning of the permeability test, as is the case where the filling rate is 0%. This means that when the flange of H-H joint is occupied with 80% of foreign substance, the H-jointed SPSPs with H-H joints attaching water-swelling materials provide better than equivalent hydraulic conductivity: $k_e = 1.0 \times 10^{-11}$ m/s. Further, even when the thickness of the water-swelling sheet was 1 mm and 80% of the flange of H-H joints is occupied with foreign substances, the equivalent hydraulic conductivity was $k_e = 2.4 \times 10^{-9}$ m/s and there was little difference from the case when there is no foreign substance. In addition, when the filling rate is 40%, the result is the same as the case when the filling rate is 80%.

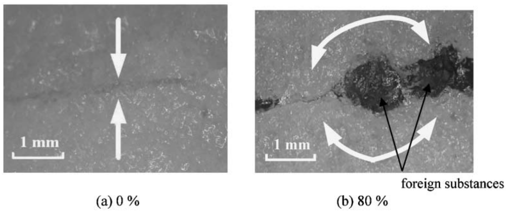


Photo. 1. Contact surface after swelling of water-swelling material

Therefore, under less than the maximum water head difference considered in a coastal waste landfill site, etc. (5 m), it was demonstrated that the H-jointed SPSPs with H-H joints with water-swelling materials attached provide superior water cut-off performance regardless of the presence of a foreign substance in the flange of the H-H joints.

We believe the reason for the above is illustrated in Photo. 1. When there are foreign substances in the flange of the H-H joints, the water-swelling material swells to encase the substance and as a result, the gap next to the substance is filled. Therefore, even when there is a foreign substance in the flange of the H-H joints, there is actually no gap just as in the case when there is no foreign substance. If the foreign substance is impermeable, there is a potential water channel next to the substance. However, because that is filled perfectly with the swelling of the water-swelling material, it is unlikely that a water channel will be created. Further, even when a permeable substance exists on the contact surface of the water-swelling material, it is very unlikely that any water channel is created because the water-swelling material swells to encase the substance. It can then be assumed that the existence of a foreign substance in the flange of the H-H joints will not have any serious impact on the water cut-off performance of the H-jointed SPSPs with H-H joints with water-swelling materials attached.

It is believed that the result of this experiment will not be affected specifically by changing the type of soil particles (or the particle diameter). The gaps between the soil particles become the bleeding channel of H-H joints when the soil particles are mixed. However, these gaps can be filled when water-swelling material is swollen. Further, even if the ''particle diameter'' of soil particles was reduced and the gaps are minute, the state of water-swelling material changes from ''solid'', ''plastic (gel-like)'' to ''semisolid (elastic)''. Hence, the minute gaps between the soil particles can be filled during the ''plastic (gel-like)'' stage, and as a result the bleeding channels can be blocked. Therefore, it is believed that there will not be any adverse effect even with soil particles of a different diameter.

THE WATER CUT-OFF PERFORMANCE UNDER ALTERNATE WETTING AND DRYING (AWD)

Summary

The coastal waste landfill sites often built along the coast near cities are exposed to influences specific to the coast, such as tides and waves, due to the conditions at the location. In other words, when H-jointed SPSPs with H-H joints with water-swelling materials attached are used as SPSPs cutoff walls in coastal waste landfill sites, the H-H joints immersed in sea water at high tide are exposed to the air at low tide. That is, the water-swelling material attached to the flange of the H-H joints around the sea surface is exposed to the air at low tide. When the swollen water-swelling material is exposed to the air, it shrinks as the water inside evaporates. As a consequence, the water cut-off performance of the H-H joints which have water-swelling material attached to them might be reduced. To assure the maximum water cut-off performance is provided by the H-jointed SPSPs with H-H joints with water-swelling material attached for practical use, the water cut-off performance needs to be quantitatively evaluated under alternate wetting and drying (AWD).

Therefore, this section discusses the water cut-off performance of the H-jointed SPSPs with H-H joints with water-swelling materials attached under AWD condition and the swelling characteristics of the water-swelling material as determined by the experiments.

Test Method

In this research, the permeability test and swelling rate test using the steel H-H flange model are implemented to evaluate the water cut-off performance of the H-jointed SPSPs with H-H joints attaching water-swelling materials under AWD condition.

Figures 21 and 22 show the details of the permeability test method in this section and the H-H flange model used in the permeability test. The permeability test method implemented in this section is as follows:

(1) Install water-swelling sheets of a predefined thickness (50×100 mm, 20×100 mm) on the top and

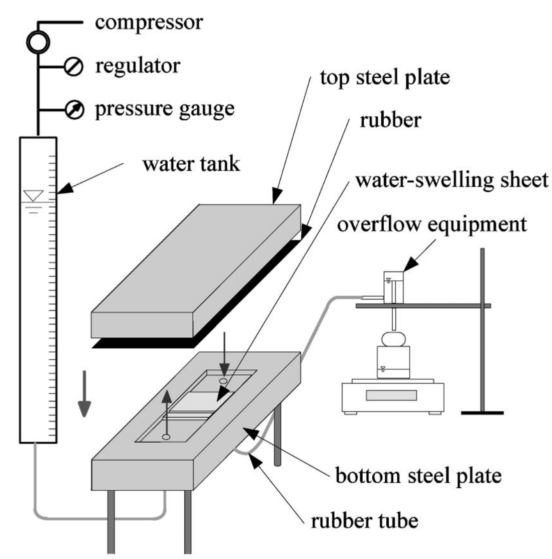


Fig. 21. Permeability test using steel H-H joint flange model to evaluate water cut-off performance under AWD condition

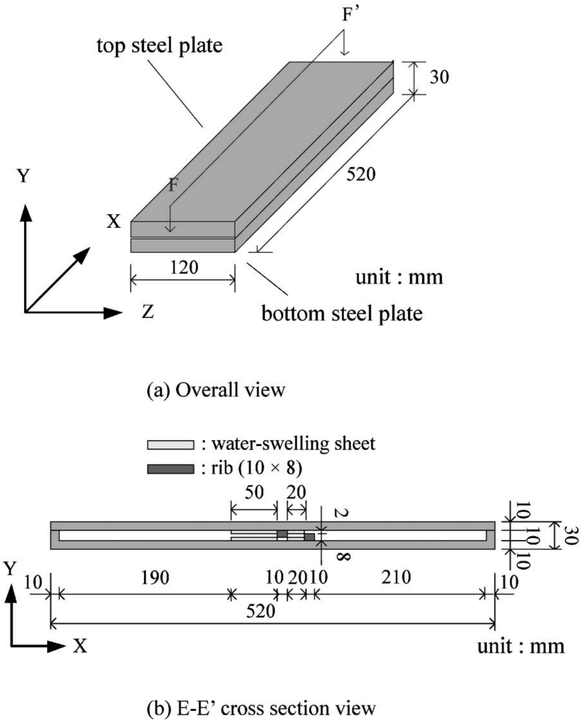


Fig. 22. Details of steel H-H joint flange model

bottom steel plates.

(2) Bolt the top and bottom steel plates together (spacing: 10 mm) to make a model H-H joint test specimen.
(3) Immerse the test specimen in plain water in the water tank and leave it for 24 hours.
(4) Adjust the water head difference to be 5 m and implement the permeability test.
(5) Measure the cumulative leakage after an hour has elapsed from the beginning of the permeability test (AWD cycle: 1).
(6) Dry the test specimen at constant temperature (20°C) and humidity (50%) for 24 hours (drying process). During the drying process, no sunlight or air is to be applied.
(7) Install the test specimen in the water tank filled with plain water and again leave it for 24 hours.
(8) Adjust the water head difference to be 5 m and implement the permeability test.
(9) Measure the cumulative leakage after an hour has passed from the beginning of the permeability test (AWD cycle: 1).
(10) Repeat steps (6) to (9) 15 times.

In this test, the measuring time to determine leakage is set to one hour. This allows thr use of the equivalent hydraulic conductivity, $k_e \leq 1.0 \times 10^{-11}$ m/s, in case the cumulative leakage cannot be checked after an hour.

Figure 23 shows the test specimen for the swelling rate test under AWD condition and the test steps are as follows:

(1) Prepare a test piece of 50 × 100 mm (water-swelling material)
(2) Measure the initial weight of the test piece and immerse it in the water tank (plain water) (AWD cycle: 1).

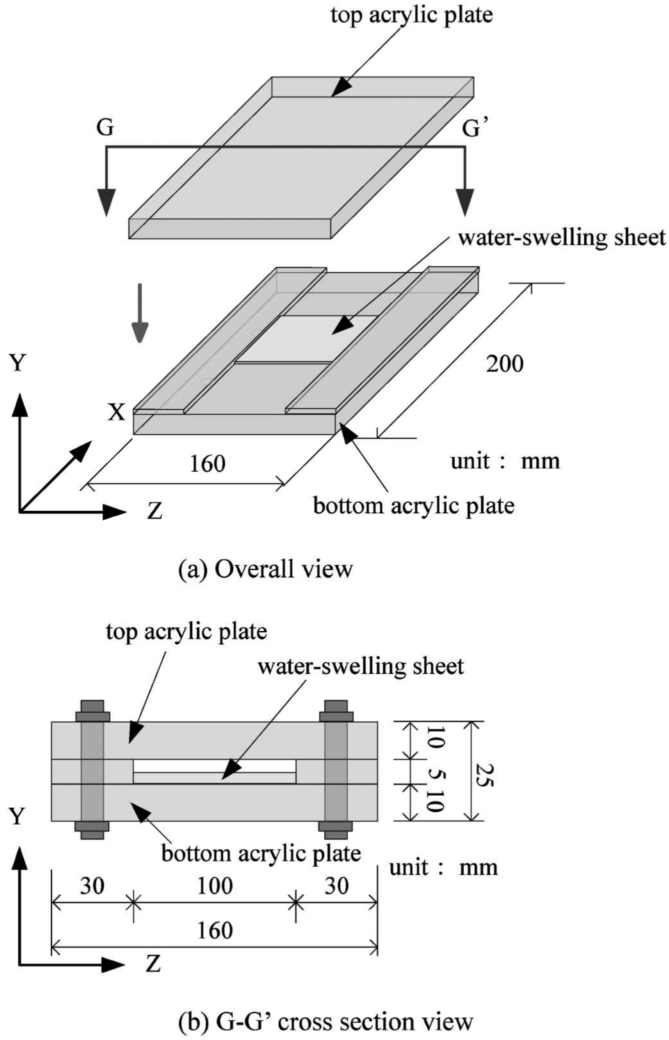


Fig. 23. Specimen for water swelling rate test

(3) After 24 hours of immersion, take the test piece out to measure the weight and calculate the swelling rate (= the weight after immersion/the initial weight).
(4) Dry the test piece for 24 hours in a room where the temperature is constant (20°C) and humidity is set at 50% (drying process). During the drying process, no sunlight or air is to be applied.
(5) Again immerse the test piece into the water tank filled with water.
(6) After 24 hours of immersion, take the test piece out to calculate the swelling rate (i.e., the weight after soaking / initial weight) (AWD cycle: 2).
(7) Repeat steps (4) to (6) 15 times.

In the above-mentioned test, the durations for the drying process and the wetting process are set to 24 hours, respectively. It is believed that the behavior evaluation when the duration of the drying process is set to more than 12 hours proves to be safer even though a usual tidal cycle is 12 hours.

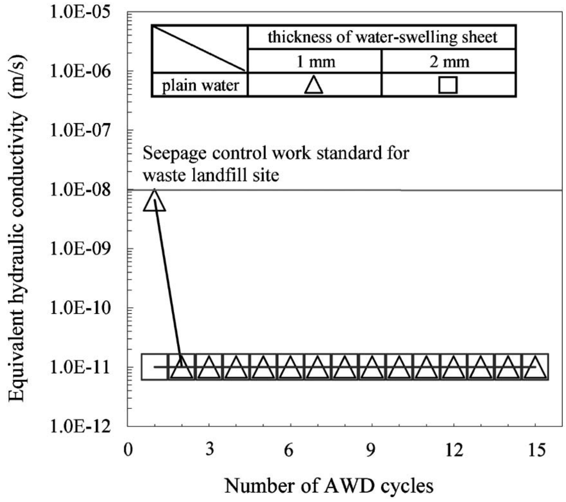


Fig. 24. Relationship between equivalent hydraulic conductivity and AWD cycle

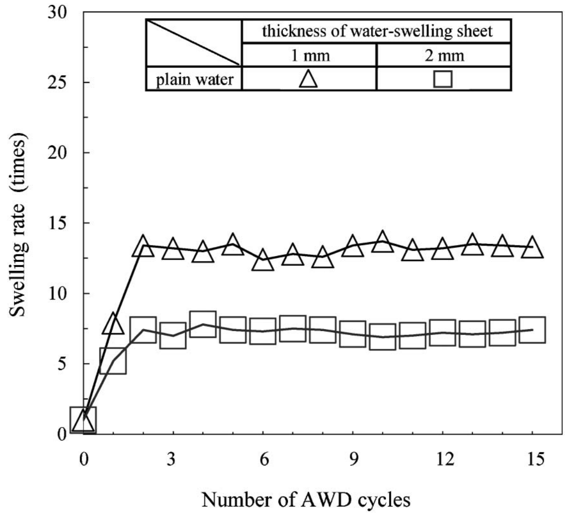


Fig. 25. Relationship between water swelling rate and AWD cycle

The Impact of AWD on the Water Cut-off Performance of the H-jointed SPSPs with H-H Joints with Water-swelling Materials Attached

This paragraph discusses the water cut-off performance of the H-jointed SPSPs with H-H joints with water-swelling materials attached under AWD conditions.

Figure 24 shows the result of the permeability test under the AWD condition where the thickness of the water-swelling sheets is 1 and 2 mm and the water head difference is 5 m. Figure 24 shows that when the thickness of the water-swelling sheet is 2 mm, there was no leakage after an hour had passed from the beginning of the permeability test at the stage of the 1st AWD cycle. Also, this trend continues after the second AWD cycle. Thus, it is concluded that when a 2 mm thick water-swelling sheet is attached, it is not affected by AWD once it has swelled and the H-jointed SPSPs with H-H joints with water-swelling materials attached provide better than equivalent hydraulic conductivity, at $k_e = 1.0 \times 10^{-11}$ m/s. Also, when the thickness of the water-swelling sheet is 1 mm, it provides equivalent hydraulic conductivity, $k_e = 6.6 \times 10^{-7}$ m/s, at the stage of the first drying cycle. Then, after the second AWD cycle, no leakage was found after an hour from the beginning of the permeability test and the equivalent hydraulic conductivity reduces to $k_e = 1.0 \times 10^{-11}$ m/s. The same result was obtained after the second AWD cycle, as was the case with the 2 mm thick water-swelling sheet. In other words, when the water-swelling sheet is only 1 mm thick, the water cut-off performance of the H-jointed SPSPs with H-H joints with water-swelling materials attached is maintained or improved.

Also, Fig. 25 shows the result of the swelling rate test under the AWD condition. Figure 25 shows that when a 2 mm thick water-swelling sheet is attached, the swelling rate is about 5 times that after the first AWD. Then, after the second AWD, the swelling rate increases to about 7.5 times and this value is kept until the 15th AWD cycle. When the thickness of the water-swelling sheet is 1 mm, the rate becomes about 8 times after the first AWD cycle, and about 14 times after the second AWD cycle. That is, whether the thickness of the water-swelling sheet is 1 or 2 mm, there is not enough swelling after the first AWD (cumulative immersion time: 24 hours). When the water-swelling material is soaked in plain water or sea water for 24 hours, Inazumi et al. (2010) reported that it swells to 15–30 times and 5–7 times, respectively, in terms of weight ratio. However, after the second AWD (cumulative immersion time: 48 hours), the swelling of the water-swelling material reaches its limit. That is, when the water-swelling sheet with either 1 or 2 mm thickness is attached, the water-swelling material cannot achieve its full swelling performance at the first AWD cycle. After the second AWD cycle the swelling rate of the water-swelling material is improved, and each water-swelling material can deliver good swelling performance. That is, considering the water cut-off performance of the H-jointed SPSPs with H-H joints to which the 1 mm thick water-swelling sheet is attached, a higher hydraulic conductivity is obtained at the first AWD cycle than at the second AWD cycle because the swelling performance of the water-swelling material is not delivered adequately at the first AWD cycle. However, after the second AWD cycle, the swelling performance of the water-swelling material is good, and as a result the water cut-off performance is improved compared to that at the end of the first AWD. Meanwhile, when the 2 mm thick water-swelling sheet is attached, the swelling rate sufficient to deliver the required water cut-off performance is obtained at the end of the first AWD cycle. The second AWD cycle increases the swelling rate to deliver even better water cut-off performance.

When the drying conditions are changed, in other words even though the water-swelling material is placed in an easy-to-dry environment (low humidity, under direct sunlight and more breeze), it is believed that there will be no effect on the equivalent hydraulic conductivity of H-jointed SPSP with H-H joints water-swelling materials attached. As a result, even though the water-swelling material that has been swollen is kept in a dry environment for 24 hours and after that in a humid environment, the swelling rate of water swelling material is maintained or increased. In other words, even though the water-swelling material is put under various drying environments, the swelling rate of water-swelling material does not decrease as long as it is given a moisture source. Therefore, it is believed that the equivalent hydraulic conductivity of H-jointed SPSPs with H-H joints has a positive correlation with the swelling rate of water-swelling material and does not decrease.

WATER CUT-OFF PERFORMANCE CONSIDERING THE DETERIORATION OF THE WATER-SWELLING MATERIAL

Summary

In a coastal waste landfill site, from the start of waste landfill to the stabilization of hazardous substances, the long-term sealing function must be ensured. In other words, the water cut-off function of the SPSPs cutoff walls applied in side seepage control works need to be maintained for a long time. This means that when H-jointed SPSPs with H-H joints with water-swelling materials attached are used as SPSPs cutoff walls, their water cut-off function should be assured from the start of their usage through to the stabilization in the landfill site. Therefore, the H-H joints should maintain their water cut-off function for a long time. Here, it is possible that in the H-H joints exposed under various conditions, the water-swelling material for water cut-off deteriorates during normal use. As mentioned above, even when the water cut-off performance of H-H joints is undermined with the deterioration of the attached and coated water-swelling material, it is easy to implement maintenance and repair of the H-H joints due to their structure. However, considering the cost for the maintenance and repair of H-H joints, it is desirable that the water cut-off performance of H-H joints is maintained for a long time. When considering the cost of maintenance and repair, it is critical to evaluate quantitatively the water cut-off performance of the H-jointed SPSPs with H-H joints when the water-swelling material attached and coated to the H-H joints deteriorates.

Therefore, this section explains the evaluation of the water cut-off performance of the H-jointed SPSPs with H-H joints with water-swelling materials attached, considering the deterioration of the water-swelling material through swelling degradation promotion permeability test(s) and strength tests of the degradation promoted swelling membrane.

Test Method

In this research, to evaluate the water cut-off performance of the flange of H-H joint when considering the deterioration of water-swelling material, the strength tests of the swelling membrane and the permeability test using the steel H-H flange model used in the previous section (*see* Fig. 22) are implemented.

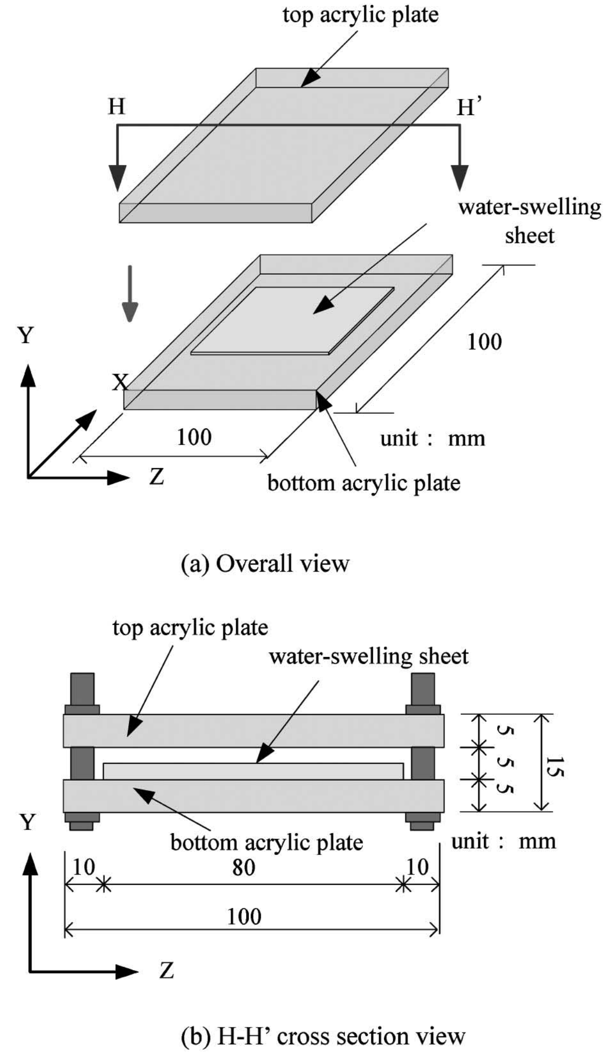


Fig. 26. Specimen for water-swelling material strength test

Figure 26 shows the test specimen used in the strength tests (Inazumi et al., 2010) of the degradation promoted the swelling membrane and its method, and the test steps are as follows:

(1) Prepare a test piece of 80×80 mm (water-swelling material).
(2) Attach the 2 mm thick water-swelling sheets to the top and bottom acrylic plates.
(3) Bolt the top and bottom acrylic plates together to make a test specimen with adegradation promoted swelling rate.
(4) Immerse the test specimen in the water tank filled with plain water (water temperature: 40°C) and leave it for 24 hours.
(5) Remove the test specimen from the water tank and measure the strength of the swelling membrane in the center of the water-swelling sheet.
(6) After the measurement, again immerse the test specimen in the water tank filled with plain water (water temperature: 40°C) again and leave it for a certain time.
(7) Repeat steps (5) and (6).

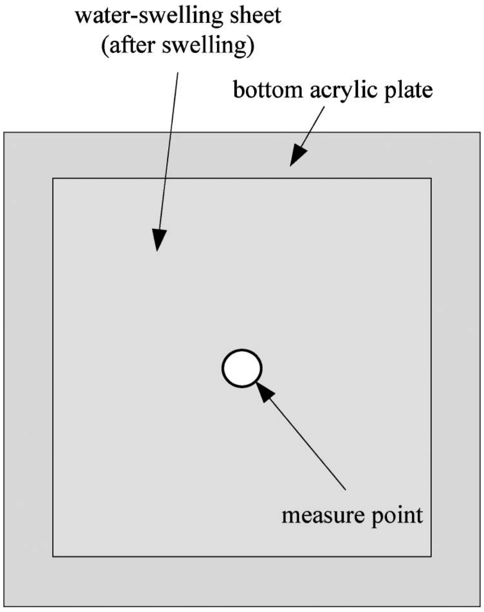


Fig. 27. Water-swelling material strength measure point

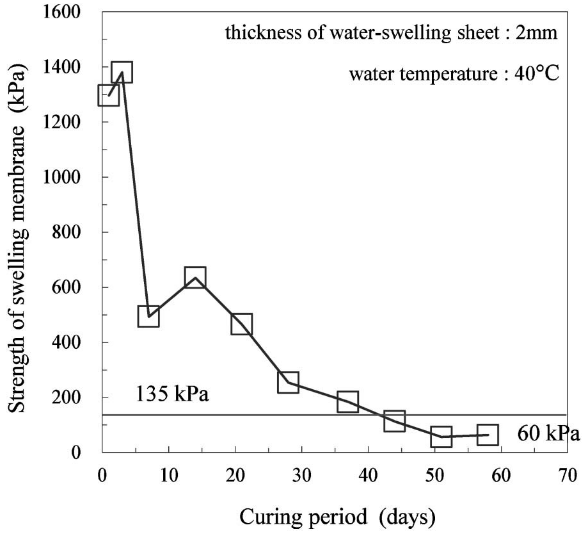


Fig. 28. Relationship between curing period and strength of water-swelling material (swelling membrane)

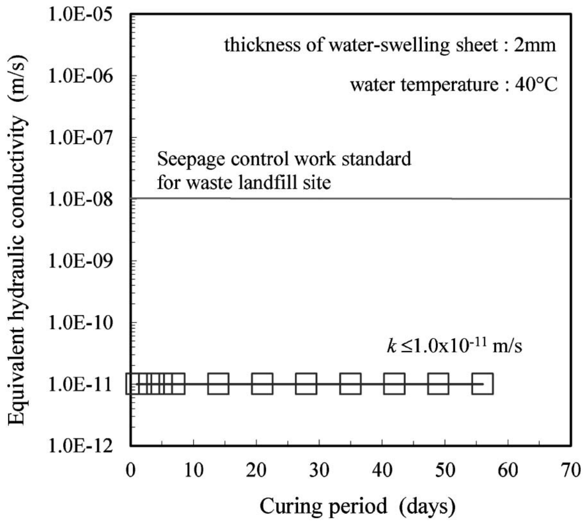


Fig. 29. Relationship between curing period and equivalent hydraulic conductivity

Figure 27 shows the measure point of the water-swelling sheet strength in the strength tests (Inazumi et al., 2010) of the degradation promoted swelling membrane.

The steps of the swelling degradation promotion permeability test described in this section are shown below:

(1) Attach water-swelling sheets of predefined thickness to the top and bottom steel plates.
(2) Bolt the top and bottom steel plates together (spacing: 10 mm) to make a test specimen.
(3) Immerse the test specimen in the water tank filled with plain water (water temperature: 40°C) and leave it for 24 hours.
(4) Adjust the water head difference to 5 m and implement the permeability test.
(5) Measure the cumulative leakage after an hour has passed from the beginning of the permeability test.
(6) Again immerse the test specimen in the water tank filled with plain water (water temperature: 40°C) and leave it for a certain time.
(7) Repeat steps (4) to (6).

In this test, the measuring time to determine leakage is set to one hour. This allows the use of the equivalent hydraulic conductivity, $k_e \leq 1.0 \times 10^{-11}$ m/s, in case the cumulative leakage cannot be checked after an hour.

Impact of the Deterioration of the Water-swelling Material on the Water Cut-off Performance of the H-jointed SPSPs with H-H Joints with Water-swelling Materials Attached

Figure 28 shows the result of the strength tests of the degradation promoted swelling membrane when the test specimen was immersed at the water temperature of 40°C. Figure 28 shows that every measured point indicates reduced strength of the swelling membrane as time passes. This shows that the deterioration of the water-swelling material develops as time passes. Also, the strength of the center of the swelling membrane reduces from 1400 to 110 kPa during 44 days of the curing period. The existing study has demonstrated that the strength of the center of the swelling membrane of water-swelling material immersed in water at a water temperature of 20°C reduces from about 930 to about 135 kPa in one year and maintains an almost constant value after that (Inazumi et al., 2010). This means that curing at a water temperature of 40°C for 44 days can simulate the curing at a water temperature of 20°C for a year. Also, after the curing at water temperature of 40°C for 51 days, the strength of the swelling membrane is about 60 kPa. That is, implementation of curing at high temperature for about 50 days can further deteriorate the water-swelling material. However, it is necessary to note that the above-mentioned reproducibility theory depends on only the results of various laboratory permeability and strength tests including tests mentioned in this section.

Figure 29 shows the result of the swelling degradation promotion permeability test when the curing was implemented at a water temperature of 40°C. Figure 29 shows when the curing is implemented at a water temperature of 40°C, there is no leakage after an hour has elapsed from the beginning of the permeability test regardless of the curing time. That is, it can be said that the H-jointed SPSPs with H-H joints attaching water-swelling materials provide an equivalent hydraulic conductivity: $k_e \leq 1.0 \times 10^{-11}$ m/s. Here, the results of the above strength tests of the degradation promoted swelling membrane demonstrate that curing at a water temperature of 40°C for 44 days can simulate curing at a water temperature of 20°C for a year. It is believed the H-jointed SPSPs with H-H joints with water-swelling materials attached can deliver the same water cut-off performance after a year has passed as that found at the initial use. Also, because the long-term water cut-off performance of the H-jointed SPSPs with H-H joints with water-swelling materials attached is predictable based on the hydraulic conductivity immediately after curing for a year, it can be said H-jointed SPSPs with H-H joints with water-swelling materials attached continue to deliver their water cut-off performance for a long time after installation. In addition, curing at high temperatures for 50 days can simulate further deterioration of the water-swelling material. That is, even when the water-swelling material has deteriorated further, H-jointed SPSPs with H-H joints with water-swelling materials attached can maintain the same water cut-off performance as that found at their initial use.

WATER CUT-OFF PERFORMANCE UNDER DEFORMATION

Summary

Japan is one of the most earthquake-prone regions in the world and the epicenters are scattered all over the country. Here, whenever an earthquake occurs, the ground around the epicenter continues to shake for a certain time and the closer you are to the epicenter, the stronger the shaking becomes. Also, after a strong earthquake occurs, some relatively weak subsequent earthquakes may occur. As mentioned above, the SPSPs cutoff walls used as side seepage control work must maintain their water cut-off function for 50 or 100 years. This means it is likely that earthquakes, small or large, will occur in the course of their normal use and that the water cut-off performance must be maintained even when repetitive shears occurs due to earthquakes. That is, to use H-jointed SPSPs with H-H joints with water-swelling materials attached as SPSPs cutoff walls, their superior water cut-off performance needs to be assured even under conditions of repetitive shear arising from earthquake activity.

Therefore, in this section, the water cut-off performance of H-jointed SPSPs with H-H joints with water-swelling materials attached is evaluated, with the kind of repetitive shear which can occur due to external forces such as earthquakes considered.

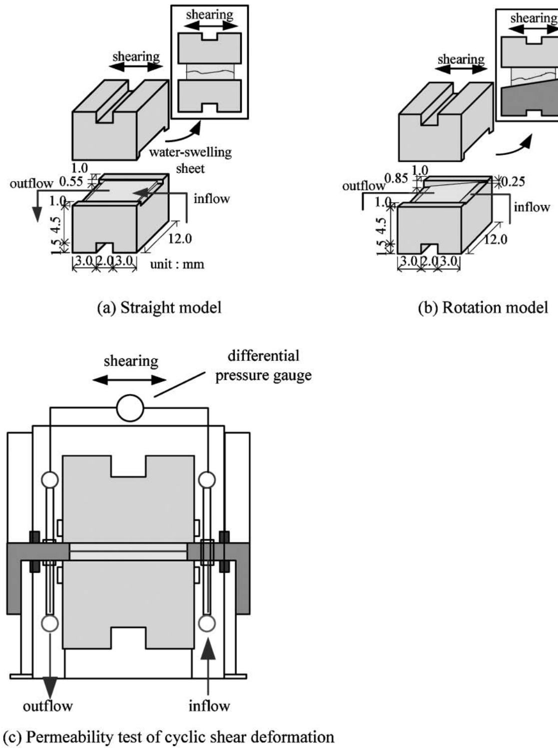


Fig. 30. Permeability test to evaluate water cut-off performance in case of repetitive shears

Test Method

In this research, to evaluate the water cut-off performance of the H-jointed SPSPs with H-H joints attaching water-swelling materials when considering repetitive shear, the permeability test using the shear permeability test machine (*see* Fig. 30) is implemented.

Figure 30 shows all the elements of the test specimen and an overview of the shear permeability test machine. The test steps are as follows:

(1) Attach a water-swelling sheet (water-swelling material) of predefined thickness to the recesses of the top and bottom steel carrier blocks.
(2) Install the test specimen into the shear box, at the position where the top and bottom steel blocks holding the water-swelling sheets are laid over each other.
(3) Cure the shear box at a constant temperature of 20°C in the water tank.
(4) Install the shear box into the shear permeability test machine.
(5) Load 1.0 MPa vertically onto the shear box.
(6) Set the maximum shear displacement to 3 mm and implement repetitive shear for predefined times with the shear speed of 1 mm/min for displacement control.
(7) Set the initial water head difference between upper stream and downstream as 1 m and implement the falling head permeability test.

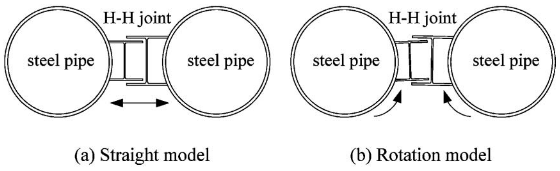


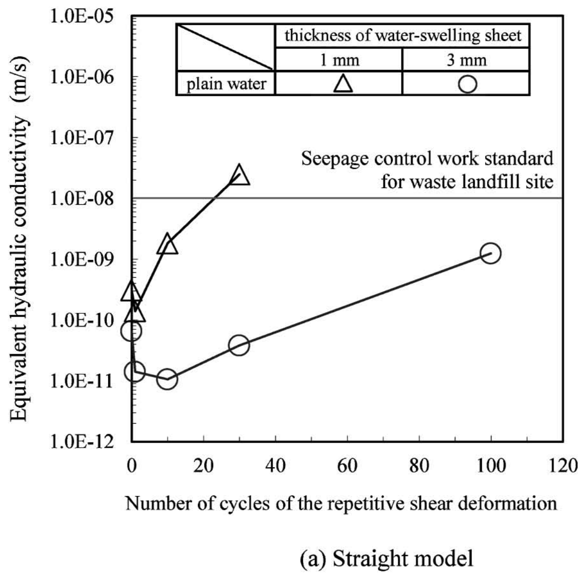
Fig. 31. Assumption of shear deformation of H-H joints

(8) Measure the cumulative leakage after an hour has elapsed from the beginning of the permeability test.
(9) Repeat steps (6) to (9)

This research assumes the shear deformation shown in Fig. 31. Depending on the strength of external forces like earthquakes, the steel parts of the joints, as well as the water-swelling material, might be deformed. However, this discussion does not assume such a large external force but a lesser external force which deforms only the water-swelling material. Further, it is necessary to keep in mind that the maximum shear displacement and initial water head difference given in this test is 3 mm and 1 m, and both these depend on the constraints of the shear permeability test machine.

Impact of Repetitive Shear on the Water Cut-off Performance of the H-jointed SPSPs with H-H Joints with Water-swelling Materials Attached

Figure 32 (a) shows the relationship between the number of cycles of the repetitive shear deformation (*see* Fig. 31 (a)) and the equivalent hydraulic conductivity, k,, when the flange interval is constant on the H-jointed SPSPs with H-H joints to which the 1 and 3 mm thick water-swelling sheets are attached. According to Fig. 32 (a), when a 1 mm thick water-swelling sheet is attached, after the first repetitive shear deformation, the initial (no repetitive shear deformation) equivalent hydraulic conductivity, $k_e = 3.1 \times 10^{-10}$ m/s, reduces to $k_e = 1.4 \times 10^{-10}$ m/s. However, as the number of cycles of repetitive shear deformation increases to 10 and 30, the equivalent hydraulic conductivity increases to $k_e = 1.8 \times 10^{-9}$ m/s or $k_e = 2.5 \times 10^{-8}$ m/s. Meanwhile, when the 3 mm thick water-swelling sheet is attached, the equivalent hydraulic conductivity is $k_e = 6.6 \times 10^{-11}$ m/s if the number of cycles of repetitive shear is zero. If the number of cycles of repetitive shear is 10, the equivalent hydraulic conductivity shows $k_e = 1.1 \times 10^{-11}$ m/s, indicating that the water cut-off function is improved. However, if the number of cycles of repetitive shear increases to 30 and 100, the equivalent hydraulic conductivity show respectively $k_e = 3.8 \times 10^{-11}$ m/s and $k_e = 1.2 \times 10^{-9}$ m/s, which shows that the water cut-off performance is undermined as the number of cycles of the shear increases. The above trend may occur because the contact surface of water-swelling material is improved through re-swelling of the water-swelling material when several cycles of shear occur (*see* Fig. 32(a)). Also, when shear exceeds a certain number of cycles, the water cut-off performance of the H-jointed SPSPs with H-H joints attaching water-swelling materials may be reduced because the swelling pressure on the contact surface of water-swelling material decreases as the number of cycles of repetitive shear increases. However, the characteristics of the equivalent hydraulic conductivity pertaining to the increased number of cycles of the repetitive shear of H-jointed SPSPs with H-H joints attaching water-swelling materials, and particularly its water cut-off performance, depend on the thickness of the attached water-swelling sheet. Therefore, when a 3 mm thick water-swelling sheet is attached, the water cut-off performance can meet the seepage control work standard ($k_e = 1.0 \times 10^{-8}$ m/s) even if the shear deformation is repeated around 100 times.



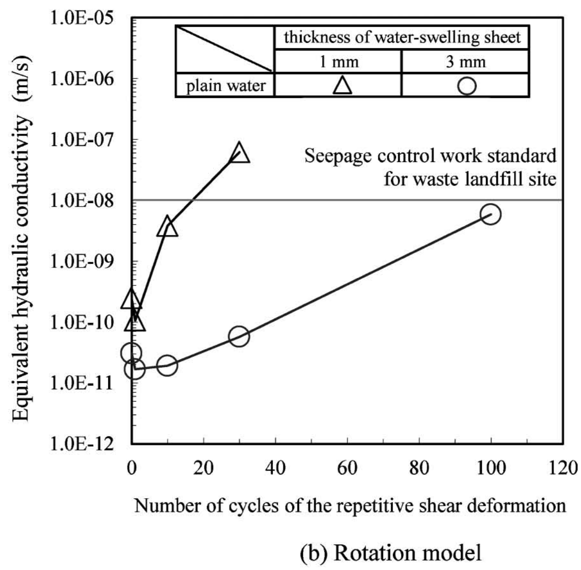


Fig. 32. Relationship between the number of cycles of repetitive shear deformation and equivalent hydraulic conductivity

Figure 32 (b) shows the relationship between the number of cycles of the repetitive shear deformation (*see* Fig. 31(b)) and equivalent hydraulic conductivity, k_e, when the flange interval changes on the H-jointed SPSPs with H-H joints to which 1 and 3 mm thick water-swelling sheets are attached. Figure 32(b) shows similar characteristics of the equivalent hydraulic conductivity (*see* Fig. 32(a)) pertaining to the number of cycles of the repetitive shear compared to H-jointed SPSPs with H-H joints attaching water-swelling materials where there is no deformation in the flange interval. That is, when the water cut-off treatment is implemented by the water-swelling material on H-jointed SPSPs with H-H joints, regardless of whether there is deformation of the flange interval or not, the same water cut-off performance can be maintained. Further, for repetitive shear deformation where the deformation occurs in the flange interval between the H-H joints, the re-swelling of the water-swelling material covers the deformation, though it depends on the thickness of the attached water-swelling sheets.

When a void is created on the contact surface of the swelling material due to the deformation of H-H joints, it is confirmed through the indoor shear permeability test that the water-swelling material used for the water cut-off treatment of H-H joints will gradually fill up the void with its re-swelling property. This re-swelling property of water-swelling material is totally different from the water cut-off treatment of P-T joints where mortar, etc. are used (Oki et al., 2003). As a result, water cut-off ability at the deformation site is also expected when considering the water cut-off function of H-jointed SPSPs with H-H joints with water-swelling materials attached in SPSPs cutoff walls. In this research, we looked at the water cut-off treatment using the water-swelling material on H-H joints. However, if there are still concerns about the water cut-off ability of the water-swelling material at a deformation site, or if the water cut-off ability barely attains the seepage control work standard, it is possible to implement double water cut-off treatment by adding mortar or bentonite water cut-off material into the of H-H joints on the H-jointed SPSPs.

CONCLUSIONS

In this research, the water cut-off performance of the H-jointed SPSPs with H-H joints with water-swelling materials attached was evaluated under various conditions; when there is damage to water-swelling material, when a foreign substance has penetrated, under repeated AWD cycles, when the water cut-off material deteriorates, and when repetitive shear deformation occurs.

The findings obtained in this research can be summarized as follows:

(1) In case of damage to water-swelling material, the water cut-off performance of the H-jointed SPSPs with H-H joints with water-swelling materials attached is reduced. However, even when 75% of water-swelling material is lost, it meets the seepage control work standard as long as the water head difference is within assumed levels in a coastal waste landfill site.
(2) A foreign substance on the contact surface of the water-swelling sheet, which is the water cut-off material, will not affect the hydraulic conductivity of H-jointed SPSPs with H-H joints with water-swelling materials attached.
(3) The water-swelling material swells to encase any foreign substance and fill the void between neighboring foreign substances.
(4) When the thickness of the water-swelling material is 1 or 2 mm and the water head difference is 5 m, AWD (Alternate Wetting and Drying) will not seriously affect the water cut-off performance of H-jointed SPSPs with H-H joints attaching water-swelling materials.
(5) When the immersion time is only 24 hours, the water-swelling material cannot deliver good swelling performance. Immersion for more than 48 hours is required to enable it to deliver good performance.
(6) Curing at high temperature promotes the deterioration of water-swelling material attached and used as coating on the flange of H-H joints.
(7) The deterioration pertaining to normal usage of water-swelling material attached and coated to the flange of H-H joints does not seriously affect the water cut-off performance of H-jointed SPSPs with H-H joints with water-swelling materials attached.
(8) Even when repetitive shear deformation occurs, it can be covered by re-swelling of the water-swelling material. However, this capability depends on the thickness of the water-swelling material.
(9) When a 3 mm thick water-swelling material is attached and coated, it meets seepage control work standards even after 100 cycles of repetitive shear.

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