Liquefaction Evaluation of Saturated Sandy Foundations with Weak Impermeable Layers

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Abstract. A series of shaking table tests were conducted to investigate the dynamic response characteristics of saturated sand soil sites with weak impermeable layers. The results revealed that the weak impermeable layer had different effects on the dynamic response of interbedded soil sites and intercalated soil sites. The thin impermeable layer in interbedded sites functions as a barrier to the vertical seepage pathway of pore water, thereby establishing a "water interlayer" beneath it. The presence of the "water interlayer" results in an increased lateral displacement of the soil at the interface with the impermeable layer, thereby significantly enhancing the capacity for energy dissipation. The presence of a thick impermeable layer, in contrast, effectively mitigates excess pore water pressure development in saturated sand, thereby significantly improving the soil's liquefaction resistance. When evaluating seismic risk in saturated sandy sites with weak impermeable layers, it is essential to consider the significant lateral displacements induced by the "water interlayer."

Key words: geotechnical engineering, weak impermeable layer, interbedded soil sites, liquefaction, shaking table test

1 Introduction

In China's offshore and the middle and lower reaches of the Yangtze River, changes in water velocity and transport capacity, as well as scouring and siltation, lead to the alternate deposition of sediments with different granular gradations in the river beds and the river bank areas, forming interbedded or intercalated soils [112]. Deposits with two types of soils alternating to form a rhythm, and when the layer-thickness ratio of the thin layer to the thick layer is greater than 1/3, it is defined as interbedded; the layer-thickness ratio is between 1/10 and 1/3, it is defined as intercalated, and the layer-thickness ratio of less than 1/10 is known as intercalated thin layer, and it is desirable to stratify the layer separately when the thickness is greater than 0.5 m, the layer-thickness ratio is defined as H_i/H_s, as shown in Fig. 1. In the 2010-2011 South

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Island earthquake in New Zealand [3], the liquefaction of the chalk and clay interbedded soil strata was mild compared to the homogeneous sand strata, and some scholars have suggested that the presence of interbedded soils can mitigate the occurrence of liquefaction to some extent.

In the past decades, most of the studies have been devoted to analyzing the liquefaction characteristics of loose saturated sandy soils [4-6], and the understanding of the liquefaction law of interbedded soil sites still needs to be deepened. Xing Yan [7] obtained two important conclusions: firstly, the vibratory pore pressure ratios in the interbedded soil can only reach 0.6-0.7, and its destruction is in the form of softening rather than liquefaction, and secondly, the vibratory pore pressure in the interbedded soil is still in the process of elevation after the stop of cyclic loading, which is similar to that of clayey soil. The results of dynamic triaxial tests of Nanjing silty clay and silt interbedded soil carried out by Chen et al. [8] similarly showed that the vibratory pore pressure of the interbedded soil still did not reach the level of the effective enclosure pressure when the axial double amplitude strain reaches 5 %, and that the interbedded soil reached the state of liquefaction if measured by the strain criterion. Mijic et al. [9] concluded that although none of the vibratory pore pressure of the interbedded specimens reached 1.0, the specimens had reached a state of liquefaction, and that the interbedded layer was limiting the presentation of liquefaction phenomena at the ground surface. Hutabarat et al. [10] innovatively proposed a parameter to quantitatively characterize the hydraulic gradient required for efflorescence, giving the conditions for the formation of surface eruption.

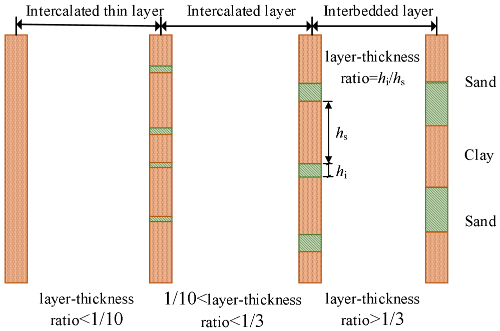

Fig. 1. Layer-thickness Ratio Schematic

It has been shown that the stratigraphic characteristics of interbedded and intercalated soils affect their liquefaction behaviors. It is worth discussing whether the dynamic pore pressures measured in the indoor unit tests of in situ interbedded and intercalated specimens are representative of the pore pressure state of the whole specimen, as the impermeable layer hinders the hydraulic connection at different locations of the specimen. If the interbedded and intercalated soils are treated as a single soil layer, although it can provide reference to a certain extent, it is not completely accurate in assessing their liquefaction characteristics and seismic safety. Therefore, it is necessary to reveal the mechanism of liquefaction effect on interbedded soil sites, especially to clarify the inhibition or amplification of liquefaction effect by weak impermeable layer.

Several shaking table tests on interbedded and intercalated soil foundations were carried out to explore the influence of the thickness of the weak impermeable layer on the liquefaction effect of interbedded soil sites by analyzing the acceleration response of the soil, dynamic pore pressure development, penetration resistance distribution characteristics, the amount of sandblasted sand, the shear stress-shear strain relationship and lateral displacements, etc.

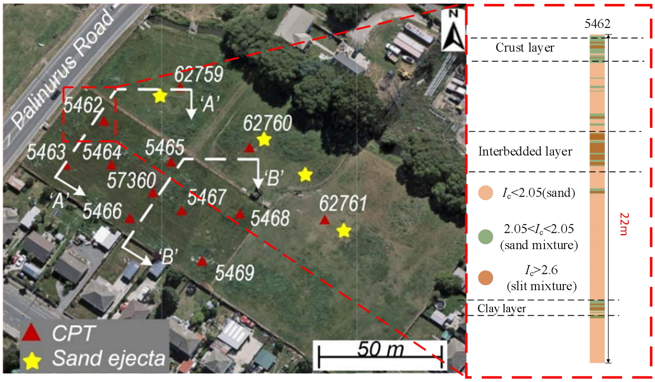

Fig. 2. An overview of the Palinurus Road site marked with CPT logs after the earthquake and a cross-section of subsoil classification measured by CPT at 5462 sites.

2 Shaking table model tests

2.1 Test Equipment and Model Preparation

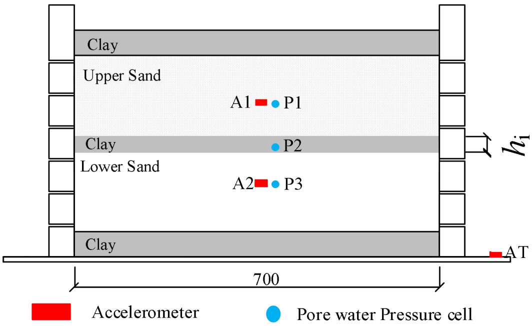

Fig. 3. The layout of sensors (Unit: mm)

Mohammad Khosravi [11] in response to the CPT data measured at Palinurus Road site in Christchurch city was obtained to be well stratified. It varies in thickness from 10.0 m to 40.0 m and consists predominantly of sand and clay, as shown in Fig. 2. The shaking table tests were designed based on the complex layered soils encountered in the field. Due to the limitation of the size of the shear box, the soil layer is simplified into layered soil, as shown in Fig. 3.

In order to visually analyze whether the weak impermeable layer will appear through cracks and ejecta phenomena under dynamic load excitation and hydraulic gradient of the upper and lower sand, different grain size ranges of sand are selected for the upper and lower sand layers of the model site. The particle grading curve of the selected sand is shown in Fig. 4. The basic physical properties of clay and sand used in the test are shown in Table.1 and Table 2.

Table.1. Physical properties of clay

Parameter	Values
Moisture content/ w(%)	46.8
Liquidity index/ I_l	1.35
Specific gravity/ G_s	2.71
Liquid limit/ w_L(%)	41.03
Plastic limit/ w_P(%)	24.76
Plasticity index /I_P	17.27
Permeability coefficient /K	1×10^{-6}

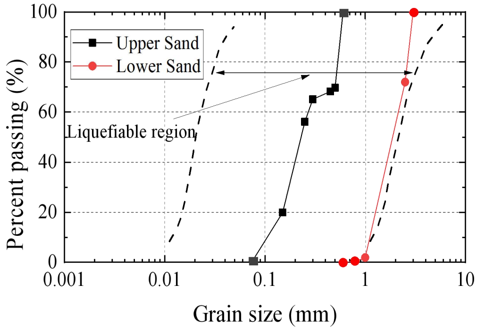

Fig. 4. Sand gradation curve

Table 2. Physical properties of sand

Position	Upper Sand	Lower Sand
Uniformity coefficient/C_u	4.67	3.37
Curvature coefficient/C_c	0.85	0.89
Specific gravity /G_s	2.72	2.72
Maximum void ratio/e_{max}	0.96	0.62
Minimum void ratio/e_{min}	0.61	0.27
Relative density/D_r	37.50%	42.10%
Permeability coefficient /K	7.4×10^{-4}	6×10^{-4}

The saturated sandy soil layer was sampled by sand pluviation method. After the preparation of the sample, it was left to consolidate for 24 h. A penetration test was carried out on the consolidated foundation model using a universal micro penetrometer. As shown in Fig. 5, the difference in penetration resistance measured at three different positions from the model box wall was small, and the change rule was consistent with the depth, which indicated that the uniformity of model sample making was good.

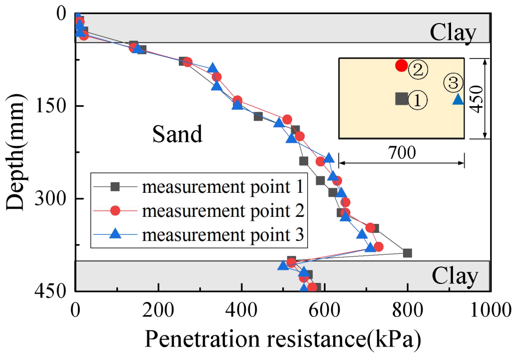

Fig. 5. Penetration resistance at different measuring points

2.2 Test Conditions

Table 3. Test conditions

Condition	Type of site	Thickness of impermeable layer h_i(mm)	Layer-thickness ratio	Peak acceleration (g)
1	Pure fine sand	0	0	0.16
2	Intercalated soil sites	10	1/17	0.16
3	Intercalated soil sites	20	4/33	0.16
4	Intercalated soil sites	30	3/16	0.16
5	Intercalated soil sites	40	8/31	0.16
6	Interbedded soil sites	50	1/3	0.16
7	Interbedded soil sites	60	12/29	0.16
8	Interbedded soil sites	80	27/16	0.16

In order to investigate the effect of impermeable layer thickness h_i on the dynamic response of the model site under dynamic loading, a total of eight sets of small shaking table tests were designed. Condition 1 is saturated fine sand site, and the remaining conditions are intercalated soil (Condition 2~Condition 5) or interbedded soil (Condition 6~Condition 8) sites, and the test conditions are shown in Table 3.The test excitation load was selected as a sine wave with a frequency of 3 Hz and the peak acceleration was 0.16 g. The test was carried out with a frequency of 3 Hz.

3 Influence of Weak Impermeable Layer Thickness h_i on Site Dynamic Response

3.1 The Influence of hi on Site Response to Excess Pore Pressure

Liquefaction is a flow phenomenon in the strength reduction process of soil[12-14], during which the excess pore pressure ratio may not reach 1.0 [15-16]. In this study, pore pressure ratio of 0.8 is defined as a sign of liquefaction in modelled foundations [17].

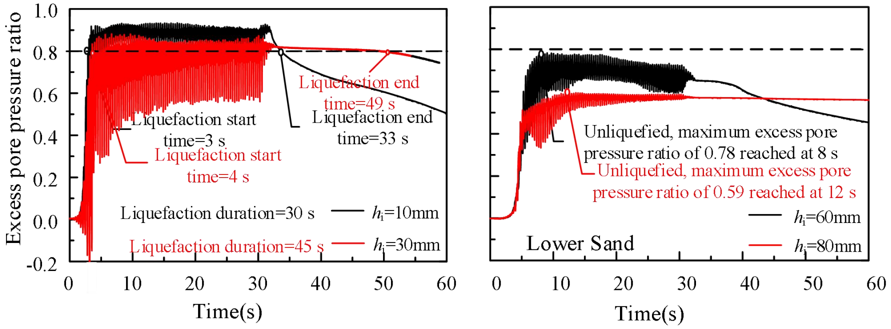

Fig. 6. Excess pore pressure ratio time histories of different conditions

As shown in Fig. 6, liquefaction occurred in the lower sand for the working conditions with impermeable layer thicknesses of 10 mm and 30 mm. And when the impermeable clay layer is thicker (T ≥ 60 mm), the pore pressure of the underlying sand in the model foundation is relatively low, and no obvious liquefaction phenomenon occurs. It can be seen that the thickness of the impermeable layer has a significant effect on the liquefaction effect of the site. Relative to the interbedded soil site with a thicker weak impermeable layer, liquefaction is more likely to occur in the intercalated soil sites with less layer-thickness ratio weak impermeable layers.

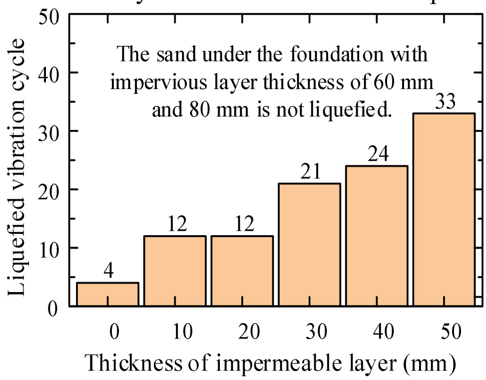

Fig. 7. Failure cycles of model foundation with different impermeable layer thickness

Fig. 7 summarizes the number of vibration times for liquefaction damage of lower sand under different working conditions. As can be seen from the figure, the thicker the impermeable layer is, the more vibration times are required for the lower sand to reach liquefaction damage. The impermeable layer structure greatly improves the liquefaction resistance of the site, and the increase in liquefaction resistance is more obvious with the increase in the layer-thickness ratio of the impermeable layer [18].

The liquefaction duration is defined as the time that lasts from initial liquefaction (r_u = 0.8) to liquefaction cessation. As shown in Fig. 8, the liquefaction duration of the lower sand in the model foundation is longer because the impermeable layer cuts off the path of sand pore pressure dissipation, and the pore water pressure of the lower sand is not easy to dissipate. Among them, the pore pressure ratio of the lower sand in the condition of the impermeable layer with a thickness of 50 mm was always higher than 0.8 before the end of the test, so it was not counted.

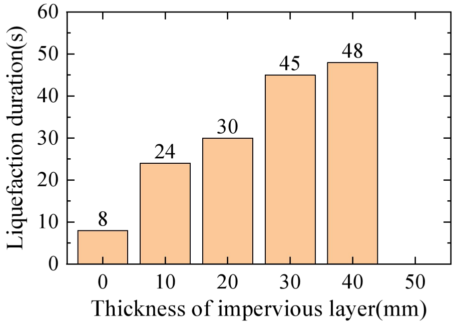

Fig. 8. Liquefaction duration of under layer sand in different conditions

3.2 The Influence of hi on Soil Lateral Displacements

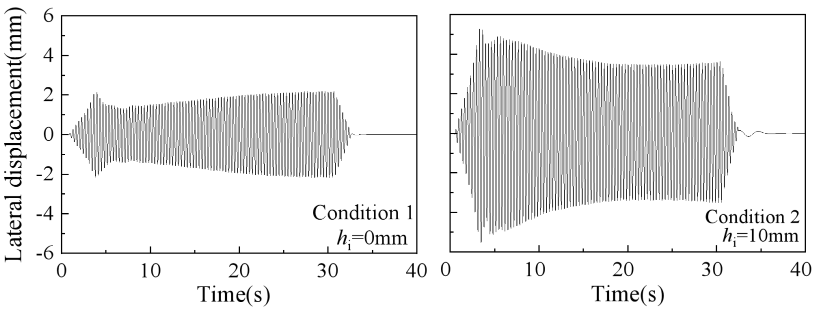

Fig. 9. Lateral displacement of upper sand

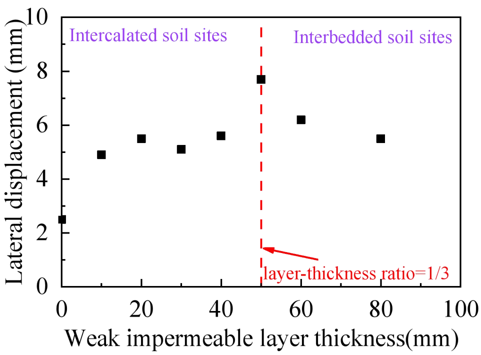

Fig. 10. Lateral displacement of underlying sand with different impermeable layer thickness

The time course curves of the lateral displacement of the upper sand for the pure fine sand site (Condition 1) and Condition 2 with an impermeable layer thickness of 10 mm are given in Fig. 9. As can be seen from the figure, the lateral displacement of the upper sand layer in the pure fine sand site is significantly smaller than that in Condition 2 with an impermeable layer.

The maximum lateral displacements of the upper sand layer for each condition are shown in Fig. 10. The maximum lateral displacements of the soils in the impermeable layer site at the same depth are larger relative to that of the pure fine sand site, which also confirms the results of previous studies. although the structure of the impermeable layer reduces the development of excess pore water pressure in saturated sand, which has a certain positive effect on the enhancement of the overall liquefaction-resistant performance of the site, it also blocks the seepage paths of the lower sand pore water from the bottom to the top, and forms the "water sandwich", which leads to a large lateral displacement of the soil at the location of the interface of the impermeable layer.

It is worth noting that there is a significant difference effect of the weak impermeable layer on the dynamic response of the interbedded soil sites. In the conditions considered in this paper, when the thickness of the weak impermeable layer is thin (less than 50 mm, which is an intercalated soil site), the lateral displacement of the sand layer gradually increases with the increase of the thickness of the impermeable layer. When layer-thickness ratio to sand layer thickness exceeds 1/3 (Condition 5 to Condition 8, which is an interbedded soil site), the lateral displacement of the sand layer gradually decreases with the increase of the impermeable layer thickness, for example, the maximum lateral displacement for the impermeable layer thickness 80 mm is about 5.5 mm, which is much smaller than that for thickness 50 mm impermeable layer thickness. This is because the thicker weak impermeable layer structure greatly reduces the pore pressure response of the saturated sandy soil and improves the liquefaction resistance of the site, thus reducing the lateral deformation of the soil caused by the "water sandwich".

3.3 The Influence of hi on Soil Shear Stress-strain Relationship

In shaking table tests, closed circles, i.e., stress-strain hysteretic curves, are formed as dynamic stress and dynamic strain are applied with dynamic loading. The hysteresis loop of liquefied soil has three basic characteristics: nonlinearity, hysteresis and strain accumulation, and the size of the hysteresis loop area can characterise the energy dissipation in the soil unit. The shear stress-shear strain relationship of the soil for a number of vibrations for some conditions is given in Fig. 11. In the figure, $W_{N=i}$ denotes the hysteresis loop area corresponding to vibration number i, i.e., the energy dissipation under the i-th vibration under single-week loading. As can be seen from the figure, the hysteretic curves at the beginning of loading is steeper, and the area enclosed by it is smaller, indicating that the energy absorbed by the soil in the vibration frequency is less. With the increase of the vibration frequency, the stiffness of the soil gradually decays, the hysteresis circle starts to tilt, the strain of the soil increases in a single week, and the corresponding area of the hysteresis circle gradually increases, indicating that the energy dissipation capacity of the soil has been improved.

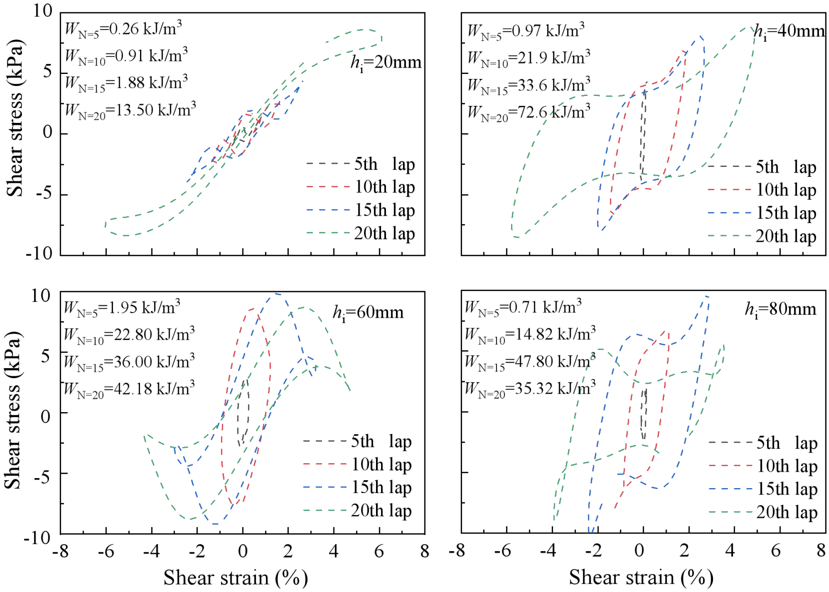

Fig. 11. Dynamic shear stress-strain relation of ground models with different impermeable layer thickness

The shear strain energy dissipation densities of the soil for each working condition are given in Fig. 12. When the number of vibrations is small, the strains produced by the foundation soil under the action of vibration load are small, and the difference in the energy dissipated by the soil under each condition is relatively insignificant; as the number of vibrations increases, the deformation of the model foundation gradually accumulates, and the influence of the thickness of the impermeable layer on the energy dissipation performance of the interbedded soils (with greater layer-thickness ratio) and intercalated soils (with less layer-thickness ratio) becomes apparent. The enhanced energy dissipation performance of the impermeable layer may be related to its special layering structure and the large lateral displacement caused by "water sandwich". This also suggests that the previous single-layer of soil pore-pressure growth model based on the energy density criterion may not be applicable to interbedded soil sites with complex soil distribution.

In addition, similar to the soil lateral displacement response law, the energy dissipation density does not increase monotonically with increasing impermeable layer thickness. When the layer-thickness ratio of impermeable layer to sand layer is less than 1/3 (intercalated soil site), the thicker the impermeable layer is, the greater the soil's unit-periodic energy dissipation density is; when layer-thickness ratio is greater than 1/3 (interbedded soil site), the soil's unit-periodic energy dissipation density decreases with the increase of impermeable layer thickness. This also confirms that there are significant differences in the effect of weak impermeable layers on the dynamic response of sites with different ranges of layer-thickness ratios.

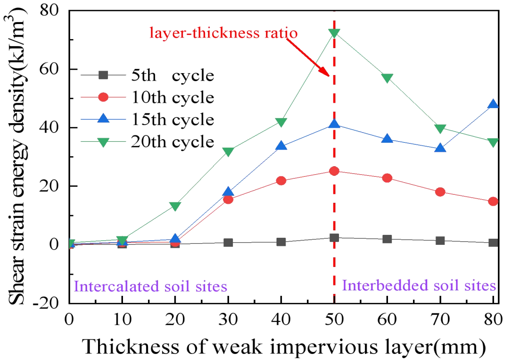

Fig. 12. Shear strain energy density of models with different thickness of impermeable layer

3.4 The Influence of hi on Soil Equivalent Shear Modulus

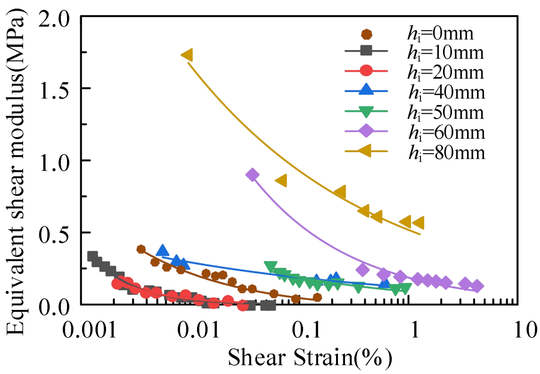

Fig. 13. Equivalent shear modulus degradation law of ground models with different impermeable layer thickness

The degradation law of the soil equivalent shear modulus with shear strain for different operating conditions is given in Fig. 13. Like saturated soil, the equivalent shear modulus of soil with impermeable layer decays exponentially with the development of shear strain. When the impermeable layer-thickness ratio to that of the sand layer is lower than 1/3, the thicker the impermeable layer is, the smaller the equivalent dynamic shear modulus of the soil is under the same shear strain amplitude. And the thicker impermeable layer is beneficial to improve the stiffness of the site with weak impermeable layer.It should be noted that the equivalent dynamic shear modulus of the soil in the pure fine sand condition is greater than that in the intercalated soil condition with a thin impermeable layer (Condition 2 and 3).

4 Conclusions

A series of interbedded soil site modelling tests were carried out using the thickness of the impermeable clay interlayer as the main variable, the following conclusions were drawn:

(1) The impermeable layer can inhibit the development of excess pore water pressure of saturated sand layer and improve the overall anti-liquefaction performance of the site. Due to the influence of the weak impermeable layer, no liquefaction phenomenon occurs in the upper sand layer of the site.

(2) In the intercalated soil site with thin impermeable layer, the impermeable layer mainly plays the role of blocking the bottom-up seepage path of pore water, thus forming a "water sandwich" under the impermeable layer, which leads to a large lateral displacement of the soil at the location of the interface of the impermeable layer and greatly improves the energy dissipation performance of the soil. In sites with thicker impermeable layers, the impermeable layer structure greatly improves the liquefaction resistance of the site, and at this time, the impermeable layer mainly inhibits the development of excess pore water pressure in saturated sand.

(3) When the layer-thickness ratio of impermeable layer to sand layer is less than 1/3 (intercalated soil site), the thicker the impermeable layer is, the greater the soil's unit-periodic energy dissipation density is，the smaller the equivalent dynamic shear modulus of the soil is under the same shear strain amplitude; when layer-thickness ratio is greater than 1/3 (interbedded soil site), the soil's unit-periodic energy dissipation density decreases with the increase of impermeable layer thickness.

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