Physical Modelling in Geotechnics

Study on trench stability of diaphragm wall foundation with enlarged part

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ABSTRACT: Significant compressive and tensile forces due to both ordinary and earthquake loads act on the foundations of ultrahigh-rise buildings with large aspect ratios, which are increasing in the urban areas of Japan. A diaphragm wall foundation with an enlarged part has been developed to handle this issue; this is a diaphragm wall foundation with an increased width at a section of the foundation near the wall tip. It is important for the trench of diaphragm wall foundation to be stable in the construction process. The purpose of this study is to evaluate the trench stability for the diaphragm wall foundation with an enlarged part. The following studies were carried out to clarify this. 1) Development of an experimental system in the centrifuge acceleration field to examine the trench stability; and centrifuge model tests to evaluate the trench stability of the diaphragm wall foundation with an enlarged part. 2) Numerical simulation by shear strength reduction FEM to simulate the centrifuge model tests.

Keywords: diaphragm wall foundation, trench stability, centrifuge model test, shear strength reduction method

1 INTRODUCTION

Significant compressive and tensile forces due to both ordinary and earthquake loads act on the foundations of ultrahigh-rise buildings with large aspect ratios, which are increasing in the urban areas of Japan. A diaphragm wall foundation with an enlarged part has been developed to handle this issue; this is a diaphragm wall foundation with an increased width at a section of the foundation near the wall tip. It is important for the trench of diaphragm wall foundation to be stable in the construction process from the ground excavation to the concrete placing stage.

The trench stability of diaphragm wall has been studied previously in several researches, in which experimental and numerical approaches have been attempted. A concept that the diaphragm wall is generally stable, since the fluid pressure such as the slurry in the trench supports the earth pressure of ground around the trench is summarized in JGS (1988). The previous evaluation methods of stability on the trench proposed by Kanatani et al. (1984) and Higuchi et al. (1994) are based on this concept. The safety factor for trench stability is calculated by the limit equilibrium method assuming a slip surface in the ground mass. However, there is difference in the calculated safety factors because the slip surfaces are assumed differently in different evaluation methods. Methods of evaluation used may have to be different in practice because the shape of slip surface on the trench of diaphragm wall is still unclear. It is also thought that those evaluation methods do not take into consideration the effect of confining pressure which acts on the soil mass along the slip surface. On the other hand, Katagiri et al. (2000) carried out centrifuge model tests to examine the trench stability of diaphragm wall. They suggested that the stability condition of slurry trenches was dependent on the length of trench, and that the lateral confining pressure around the sliding block decreased at the failure condition. An analytical study of trench stability was performed by Ishii et al. (2001). They conducted a 3-D elasto-plastic FEM combined with a shear strength reduction method to estimate the global safety factor. Note that these previous studies have been conducted to obtain the trench stability of the diaphragm wall without an enlarged part.

It is therefore necessary to evaluate the trench stability on the diaphragm wall foundation with an enlarged part because the failure mechanism and the applicability of analysis method are still uncertain. Thus the purpose of this study is to evaluate the trench stability on the diaphragm wall foundation with an enlarged part. The following studies were carried out to grasp the trench stability:

1) Development of an experimental system in the centrifuge acceleration field to examine the trench

stability, and centrifuge model tests to evaluate the trench stability of the diaphragm wall foundation with or without an enlarged part in a sandy model ground.

2) Numerical simulation by using shear strength reduction FEM to evaluate the centrifuge model tests.

2 CENTRIFUGE MODEL TEST

2.1 Centrifuge apparatus

The Aichi Institute of Technology Centrifuge (AIT Centrifuge) was used in the model test described in this paper. This centrifuge is a beam type with a pair of parallel arms that hold platforms on which the model container and a counterbalance weight are mounted as shown in Fig. 1. Effective radius of rotation is 1.36m, which is the distance from the rotating shaft to the platform base. The surface of swinging platform is always normal to the resultant acceleration of the centrifuge acceleration, *n*G, and the earth's gravity. The specifications of AIT Centrifuge are summarized in Table 1.

2.2 Condition of centrifuge model tests

A schematic view of test apparatus is shown in Fig. 2. The dimensions of the steel container are; width *B*=460mm, height *h*=460mm and length *l*=200mm. The model ground was prepared by air-pluviation method using Silica sand No. 7 to achieve a relative density of D_r=60%. Figure 3 indicates the grain distribution curve of the Silica sand used, and its physical properties are also shown in Table 2. The model ground is saturated after preparing the dry sand ground. All the tests were

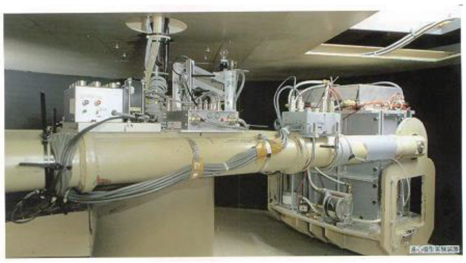


Fig. 1 Aichi Institute of Technology centrifuge

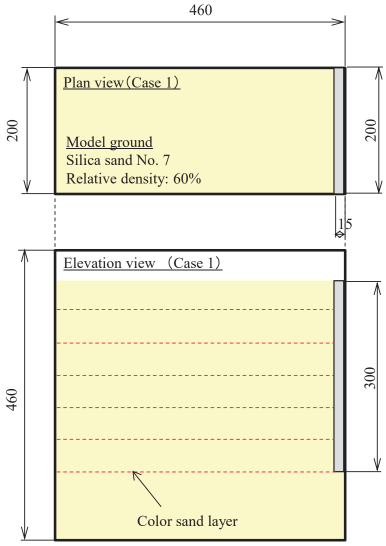
Table 1 Specifications of Aichi Institute of Technology centrifuge

Outer diameter of arm	2.72m
Height of arm	1.00m
Effective radius of platform	1.36m
Maximum payload	15g-t
Payload weight	0.2t (75g)
Platform space	0.6m*0.5m
Test model height	600mm

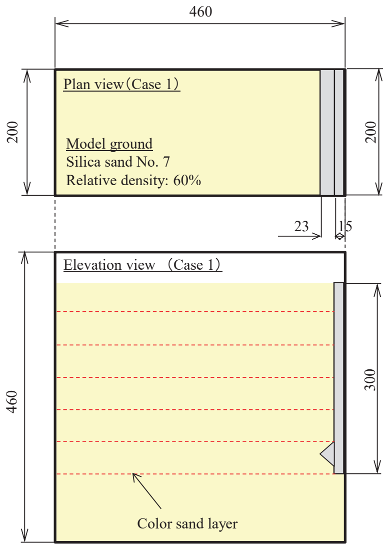
conducted in saturated sand conditions under 50G. The model diaphragm wall foundations are assumed in a two-dimensional condition considering symmetry the prototype diaphragm wall foundation in the planar shape.

The shape of model diaphragm wall is simulated by a thin plastic (thickness *t*=0.1mm). This thin plastic represents mud membrane inside the trench in the actual construction process.

The experiments proceed in such a way that the support fluids in the model trench decreases when a target centrifuge acceleration of 50G is reached. Here, the support fluids used is a saline water (Specific gravity, 1.05) which is equivalent to actual support fluids such as bentonite fluids and polymer fluids. The initial water level before the support fluids drainage is set 0.5m above



(a) Without an enlarged part



(b) With an enlarged part

Fig. 2 Schematic view of test apparatus

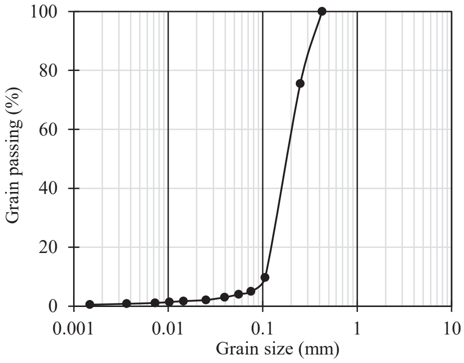


Fig. 3 Grain size distribution of silica sand No.7

Table 2 Physical properties of silica sand No. 7

Soil particle density ρ_s (g/cm^3)	2.654
Mean diameter D_{50} (mm)	0.185
Maximum void ratio e_{max}	1.193
Minimum void ratio e_{min}	0.698

Fig. 4 Low-flow type solenoid valve

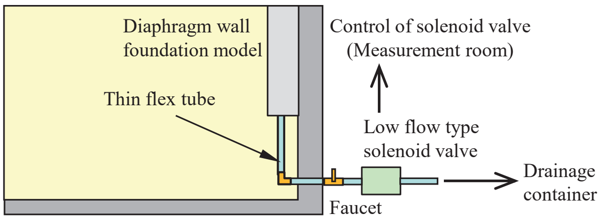
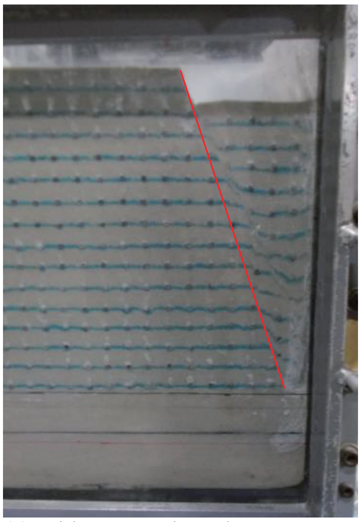
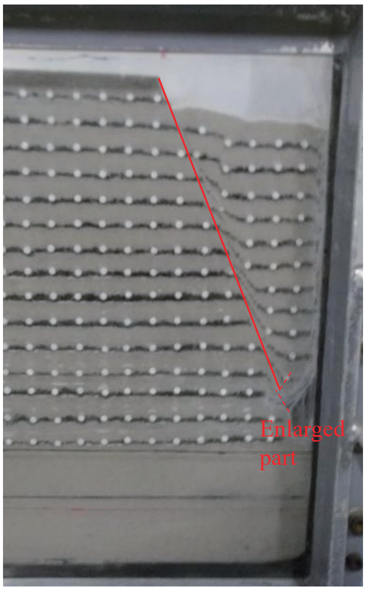


Fig. 5 Experimental system of support fluids drainage



(a) Without an enlarged part



(b) With an enlarged part

Fig. 6 Failure mode of centrifuge model tests

the ground surface in the prototype scale. A low-flow type solenoid valve shown in Fig. 4 is used to drain the support fluids in the model trench of diaphragm wall foundation. A schematic diagram of the experimental drainage system of the support fluids is shown in Fig. 5. The drainage line is arranged at the bottom of diaphragm wall foundation model which is connected to the low-flow solenoid valve. The support fluids is drained out by controlling the solenoid valve from the measurement room. The development of drainage system in the centrifuge acceleration field is one of the purposes of this study to in the examination of trench stability.

2.3 Results of centrifuge model tests

Figure 6 indicates the failure modes obtained from the centrifuge model tests. The deformation of the model ground progresses as the support fluids in the model trench decreases. It is seen in Fig. 6 that a slip line occurs when the trench and the model ground fail. The shape of the slip lines is a straight line in both cases. The angles of slip line which are measured manually are 72 deg. for diaphragm wall foundation without and 66 deg. for diaphragm wall foundation with an enlarged part, respectively. Here, the active failure angle is calculated as 63 deg. by using internal friction angle obtained from the triaxial compression test for silica sand No. 7.

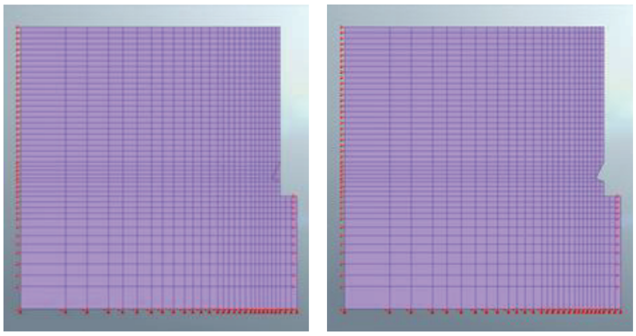
3 SIMULATION OF CENTRIFUGE MODEL TESTS

3.1 Numerical method

Shear Strength Reduction-FEM (SSR-FEM) which is included MIDAS GTS-NX is an elasto-plastic FEM simulation scheme including the shear strength reduction method and can evaluate global safety factor that is defined by limit equilibrium methods without assuming a slip surface. In addition, since deformation problems have to be considered in elasto-plastic FEM simulations, SSR-FEM can deal with complicated conditions, taking into account the confining pressure which acts on a sliding earth mass.

The purpose of this analysis is to simulate the results of centrifuge model tests described in section 2. The model trench is a quadrant of the prototype scale considering symmetry. It is assumed that the failure of soil is defined by the Mohr-Coulomb's failure criterion. The iteration process is based on the modified Newton Raphson method.

Figure 7 indicates the schematic view of FEM analysis model which is constructed in full scale model. The model is divided into the model ground and the model trench. The parameters of ground and the support fluids used in the analysis are shown in Table 3. The material parameters of cohesion *c*', internal friction angle ϕ' and elastic modules E_{50} is determined based on the results of triaxial compression tests. The Poisson's ratio is obtained from the result of K_0 consolidation test. The density of the model ground is calculated by using void ratio *e* and specific gravity G_s. In the boundary condition, the displacement on the bottom surface is fixed in all directions, while back surface and right side surface is confined in the horizontal (x) direction.

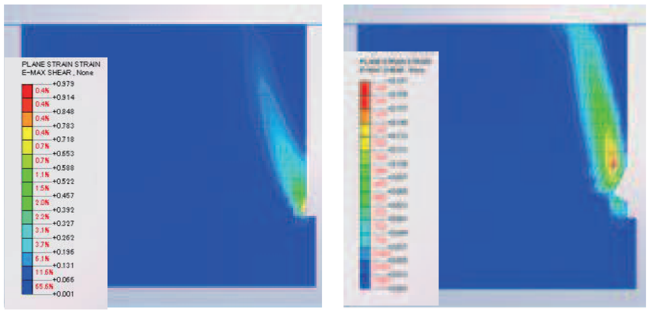


(a) Without an enlarged part (b) With an enlarged part

Fig. 7 FEM analysis model

Table 3 Analytical parameters

Properties	Ground	Stable liquid
Density (g/cm^3)	1.9	1.05
Cohesion (kN/m^2)	8	
Inernal friction angle (deg.)	37	
Elastic modulus (kN/m^2)	8837	
Poisson's ratio	0.277	



(a) Without an enlarged part (b) With an enlarged part

Fig. 8 Failure modes of centrifuge model tests

3.2 Results of simulation

Figure 8 presents the contour of maximum shear strain when the difference in water level ΔH is -0.5m. This means the support fluids is lower than the ground water level at the ground surface. Fig. 8 shows the deformation immediately after the failure. According to the contour of maximum shear strain, deformation toward the ground surface was confirmed from the model diaphragm wall foundation. In addition, it is seen that the shape of indicated slip line is a straight line. This trend agrees with the results of centrifuge model test as shown in Fig. 6. In case of diaphragm wall foundation with an enlarged part, it is also observed that the maximum shear strain becomes large near the enlarged part. It is clear that the deformation behavior for the centrifuged model test can be simulated by SSR-FEM described in this section.

4 CONCLUSIONS

The purpose of this study is to evaluate the trench stability on the diaphragm wall foundation with an enlarged part. The following findings were obtained from this study.

1) An experimental system in the centrifuge acceleration field to confirm the trench stability of diaphragm wall foundation was developed.
2) The failure mode of diaphragm wall foundation with or without an enlarged part was examined by the centrifuge model tests. It is suggested that the failure mode is in a straight slip line close to the active failure line.
3) The failure mode of FEM simulation agrees with that of centrifuge model tests, suggesting that the results of centrifuge model tests can be simulated by using SSR-FEM.

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