MODELING OF CAISSON QUAY WALL IN THREE DIMENSIONAL ANALYSIS OF LIQUEFACTION-INDUCED FLOW

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ABSTRACT :

Interface element to be employed in three-dimensional analysis of liquefaction-induced flow is investigated and proposed. The Koshien-hama fill land, Kobe city, where significant liquefaction-induced flow was observed during the 1995 Kobe earthquake was analyzed at first, in order to see effectiveness of a ordinary three-dimensional analysis. It showed that displacement is very small and unrealistic especially at the corner of quay walls. Two factors are found to be responsible. The one is axial stiffness of quay wall as well as tensile stiffness of soil element. Another is separation of soil; soil element at the corner must be separate if caissons in two sides move into different directions, but it is impossible as there is only one node at the corner. There should be no stiffness between caissons in the actual situation but is connected in FE analysis, and separation is not formulated in ordinary FEM. Then use of interface element is examined. It is concluded that interface element, which can consider no-tension behavior, is necessary not only between caissons and between caisson and adjacent soil, but also between soil elements. If interface element is not installed relevantly, displacement near the corner becomes small. Moreover, displacement in the ordinary place is also constraint and is small.

KEYWORDS: liquefaction, liquefaction-induced flow, 3-dimension, quay wall, interface element, no-tension

1. INTRODUCTION

Liquefaction-induced flow is phenomena associated with soil liquefaction, sometimes resulting in large displacement of order of several meters (JGS, 1999). It was first found to occur in the Noshiro city, Japan, during the 1983 Nihonkai-chubu earthquake (Hamada et al., 1986). The technique to measure residual displacement, comparison of aerial photos before and after the earthquake, was then applied to many past earthquakes as well as subsequent earthquakes, and evidences of liquefaction-induced flow were also collected. As a result, liquefaction-induced flow is found not to be extraordinary phenomena but have commonly occurred in many earthquakes.

The term "liquefaction-induced flow" became familiar with citizens as well as geotechnical engineers after the 1995 Hyogoken-nambu (Kobe) earthquake. Almost all caisson quay walls in the Kobe city moved towards the sea because of soil liquefaction in the supporting ground (PHRI, 1997), which caused large horizontal displacement in the backfill ground (Ishihara et al., 1995; Hamada et al., 1995) and damage to underground structures such as pile (BTL Committee, 1998). After that, many design specifications have considered it (e. g., JRA, 2002; Railway Technical Research Institute, 1999).

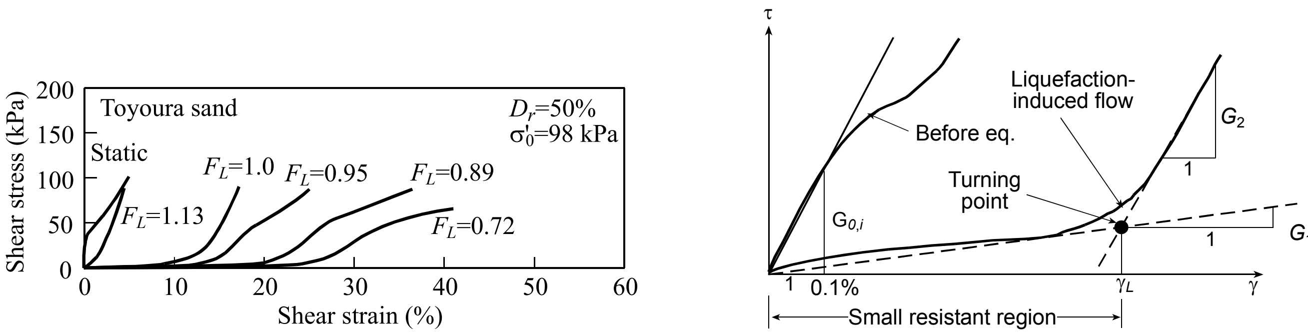
Liquefaction-induced flow has occurred at two geotechnical conditions (JGS, 1999). The one is a case where ground surface or liquefiable ground tilts. In Japan, displacement of order of several meters has observed at very small gradient such as 1/100 or less. The other is a case where there is open space such as bank protection or shore protection near the river or sea. Liquefaction-induced flow in Kobe city corresponds to this case.

In almost all research as well as design specifications, liquefaction-induced flow is treated as two-dimensional phenomena. If quay wall is sufficiently long, treatment as two-dimensional phenomena may be justified. The authors investigated three-dimensional effect on liquefaction-induced flow at Noshiro city (Yasuda et al, 2005), which is the case that ground surface and liquefied layer have slope, and showed that, depending on the geotechnical conditions, three-dimensional configuration must be considered.

In this paper, we investigated three-dimensional effect on the case of the ground back to the quay wall, and propose a method to make three-dimensional analysis relevantly.

2. METHOD OF ANALYSIS

A simplified procedure, ALID (Analysis of Liquefaction-Induced Displacement) (Yasuda et al., 1999) is used to analyze liquefaction-induced flow. This method focuses on only state after liquefaction-induced flow. Since there is no earthquake or dynamic load after liquefaction-induced flow, only gravity load works. Therefore, displacement after liquefaction-induced flow can be obtained by an analysis using mechanical properties after liquefaction. ALID suggests two methods. In the first method, residual displacement is obtained as the difference of two switch-on-gravity analyses in which mechanical properties before the earthquake and those after liquefaction-induced flow is used. This method is called switch-on-gravity method. An alternate method is called stress-relaxation method. Stiffness before the earthquake is evaluated by a layer construction analysis, which enables a more complex ground condition than before by considering the process of construction or development of ground or land. The stress-strain relationship is replaced from the one before the earthquake into the one during liquefaction-induce flow keeping displacement constant at first. This process requires constraint force at each node so as to keep displacement unchanged against the change of stress-strain relationships. If we release this constraint load, the ground moves into new equilibrium state under the new property, resulting in large horizontal as well as vertical displacement. This procedure is more complicated in stress-relaxation method, but it has advantage to be able to consider change of initial stress caused by construction process.



(a) Test (Yasuda et al., 1999) (b) Model in ALID

Figure 1 Stress-strain curve after liquefaction

Figure 1(a) shows stress-strain curve during liquefaction-induced flow (Yasuda et al., 1999). These curves are shown in Figure 1(b) schematically. Thick solid lines are stress-strain relationships before the earthquake and during liquefaction-induced flow. The latter stress-strain curve is modeled into a bi-linear model with stiffness G_1 and G_2 in ALID. This model shows concave shape, and the region with modulus G_1 is called small resistant region. The value of G_1 is very small because it corresponds to flow as shown in Figure 1(a), but it is not zero even during liquefaction. Stiffness increases as soil particle forms new structure at large strains, which is expressed by line with stiffness G_2. These stiffnesses depend on the amount of cyclic load after the liquefaction. The amount of loading is represented by index F_L, a well known parameter as liquefaction resistance factor. The F_L value becomes smaller as amount of loading increases. Then G_1 becomes smaller and region of small resistant region increases. Stiffness during liquefaction-induced flow is shown in Figure 2 (Yasuda et al., 2005), and is expressed by means of minimum of mean square root method as

$$G_1 / \sigma'_c = a \exp(-\exp(b(R_L - c))) \qquad (1)$$

where σ'_c is initial effective confining stress, R_L is liquefaction strength, and a, b and c are parameters that are functions with respect to F_L. Stiffness calculated from Eqn 1 is also shown in Figure 2.

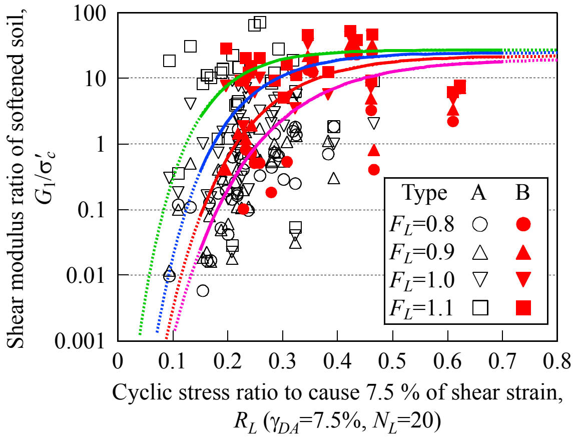
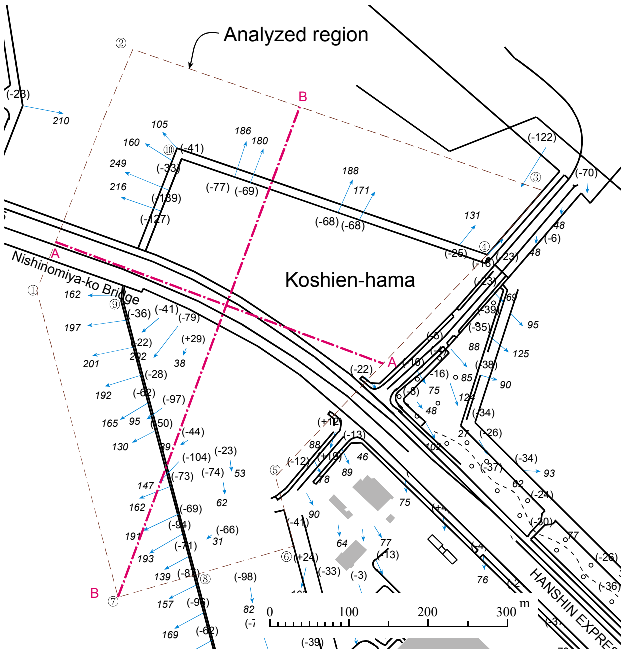


Figure 2 Shear modulus during liquefaction-induced flow



(a) Aerial photo of Nishinomiya-ko Bridge (b) Residual displacement
Figure 3 Koshien-hama fill land

3. ANALYSIS AT KOSHIEN-HAMA

As an example to show three-dimensional effect, Koshien-hama fill land, shown in Figure 3, is chosen. Figure 3(a) shows Koshien-hama and Nishinomiya-ko Bridge which fell down at the Koshien-hama, and Figure 3(b) shows map of the area and residual displacement caused by the 1995 Kobe earthquake (Hamada et al., 1995). Displacement of quay walls is about 2 meters. As the land has three sides facing to the sea, three-dimensional effect is expected to occur if it exists. The area enclosed by dashed line in Figure 3(b) is chosen as analyzed region, which is composed of six sides among which three sides face to the sea. The seabed up to 100 m from the shore is considered to be analyzed region. Boundary conditions at the side is set fixed in the horizontal direction, and is free in vertical direction.

The ground down to GL-25 m is analyzed. Soil profiles are determined by simplifying the soil profile measured during the construction of the Nishinomiya-ko Bridge and Hanshin Highway (Hanshin Expressway Public Corporation, 1997), and are shown in Figure 4. Caisson and surrounding ground are modeled into Figure 5. Figure 6 shows isoparametric view of the FE model; total number of element and node are 74294 and 85611, respectively. Three-dimensional multi-purpose computer code DIANA (TNO, 2005) is used to analyze residual displacement after liquefaction-induced flow. The procedure is already described as switch-on-gravity method in ALID in the previous section.

Displacement of the quay wall is shown in Figure 7 with measured displacement. In general, displacement by ALID agrees with observed one well, but there are some differences if investigated in detail. For example, displacement is very small at the left edge. There is a bridge pier of the Nishinomiya-ko bridge very close to the quay wall, and it is obvious that existence of the pier constraint displacement of the quay wall in front of it.

Another difference is seen at the corner or intersection of quay walls. Displacement becomes very small near the corner in the analysis whereas it is of same order with ordinary sides in the actual situation. The reason of this small displacement is also clear. Let consider, for example, a corner of two quay walls. If one caisson is going to move toward the sea, it pulls another caisson in the axial direction, but this movement will be prevented because axial stiffness of the caisson is very large. It is, however, noted that interface element is installed between caissons at every 10 m in this analysis. Therefore, the problem seems not so simple, and it will be discussed in the next section.

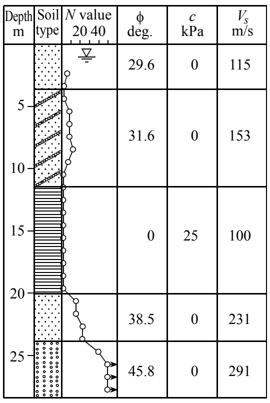


Figure 4 Soil profiles

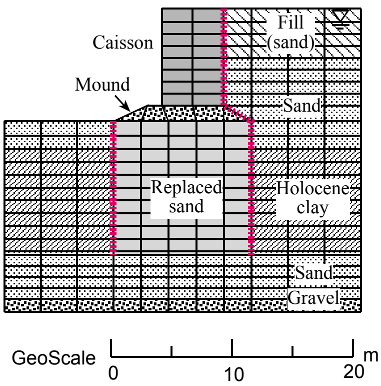


Figure 5 Details of model near caisson

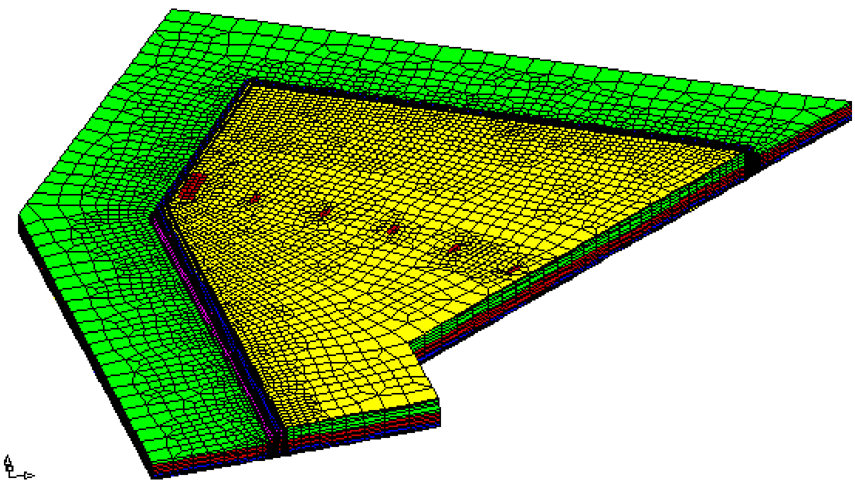


Figure 6 FEM model in three-dimensional analysis

4. EFFECTIVENESS OF INTERFACE ELEMENT

When liquefaction-induced displacement occurs in the fill with at least two sides, it is usual that damage a the corner or intersection of caissons occurs. Therefore, zero or small displacement at the corner, shown in the preceding section, is not realistic. There are several reasons why displacement at the corner is small. The first reason is axial stiffness of the caisson as discussed before. Since separation of the caisson in the axial direction is constraint if adjacent elements have common node. In order to escape from this constraint, we placed interface element in the previous analysis in 10 m distance. The result in the preceding analysis shows, however, consideration only it cannot solve the problem.

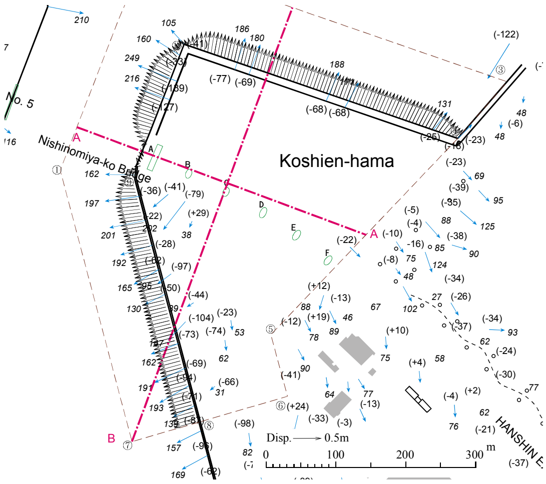


Figure 7 Horizontal displacement of caissons

The next reason may be tensile behavior of soil. Since ALID is a simplified method, it does not consider nonlinear behavior. It means that soil shows rigidity against tension. This tensile stiffness may constrain displacement by the same reason as caisson.

If there space or separation appears between caissons, it must occur in soil elements, but it is not considered in the preceding analysis. A more complicated behavior occurs at the corner. If, for example, two side at the corner moves independently towards the sea, the soil element that includes corner should separate, but ordinary finite element model cannot express this kind of behavior. This is the third reason. This seems to be similar with previous because tensile failure of soil is not considered. It is, however, quite different phenomena in the theory of finite element method. Finite element method is a technique to obtain approximate solution of continuum. It means that discontinuous behavior described above cannot be expressed in the ordinary finite element technique, and we should move another tools to consider discontinuity. Several tools have been proposed, but they are still not in practical use. From the point of view of engineer, finite element method is familiar and engineers have good experience on its use. Therefore, improvement from the ordinary finite element method is relevant if this problem can be solved. Use of an interface element seems to be a solution of this problem, and we examine it.

In order to solve the problem in the framework of finite element method, we employ interface element a more flexible way than the previous analysis by placing interface elements between soil elements as well as between caissons and between caisson and adjacent element. Then next problem arise; how dense or how many interface elements are necessary?

For the simplicity, we changed analyzed model from that in Figure 6 to simpler model shown in Figure 8. Soil profiles, shown in Figure 9 as FE mesh near the caisson, is almost the same with previous. The plan is 200 m x 200 m, in which 3/4 is sea and 1/4 (third quadrant) is fill land. Caisson is modeled simply as shown in Figure 9.

Interface elements are placed at every 10 m distance, which is shown as dashed line in Figure 8. Two kinds of interface element is used. The one is rigid element by which displacement at two adjacent element nodes becomes identical. In other words, it corresponds to the case where interface element is not installed. The other is called no-tension element as it works same as rigid interface element if two adjacent elements tends to overlap, and zero stiffness as they separate.

Three cases are examined. Only rigid interface element is used in the first case. As described, this case is identical with the case that there is no interface element. No-tension element is placed only between the caisson and adjacent soil element at the back of the caisson in the second case. All the interface elements are no-tension elements in the third case. They are distinguished as rigid, no-tension1 1, and no-tension 2, respectively. In addition, two-dimensional analysis is also made to see three-dimensional effect. It is noted that constitutive model is not linear in the interface element; therefore, the analysis is not an elastic analysis, but nonlinear analysis.

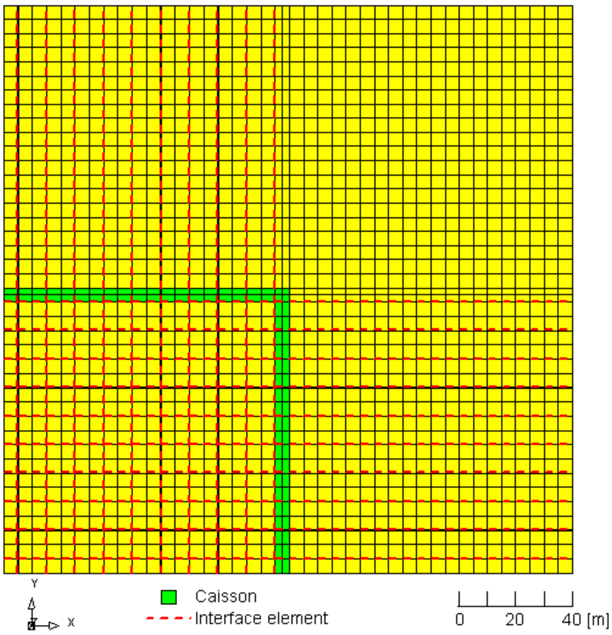


Figure 8 Plan of simple FE model

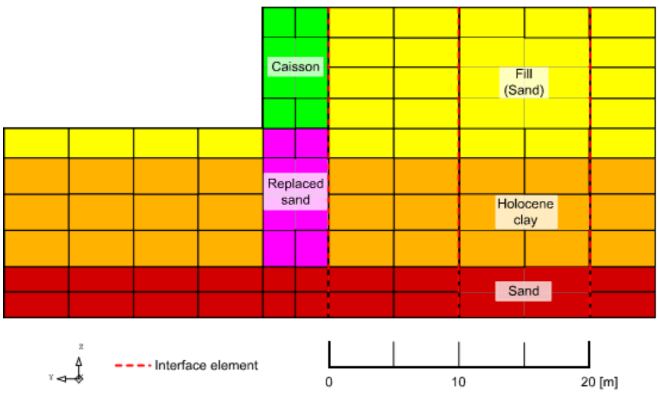


Figure 9 FE mesh near caisson

Displacement of quay wall is shown in Figure 10, where result of two-dimensional analysis is also shown. At first, results by rigid and no-tension 1 cases are almost identical, which indicate that the backfill ground push the caisson. In other words, horizontal earth pressure increases from initial state (smaller than overburden stress) to the overburden stress in the transient process to liquefaction, and it pushes caisson. It also means that liquefaction of replaced sand has less effect on displacement of caisson, because separation between the caisson and adjacent soil is expected if the caisson moves first.

We can, however, see the shortage of the conventional method. Displacement of the caisson at the corner is nearly zero. In addition, a more significant shortage is seen by comparing the displacement by two-dimensional analysis. Displacement by three-dimensional analysis is much smaller than that by two-dimensional analysis; it is about 60 % at the largest. It indicates that conventional three-dimensional analysis evaluates displacement too small.

On the other hand, in the no-tension 2 analysis, displacement is the same with that by two-dimensional analysis. In addition, displacement at the corner is not zero, but as large as 70 % of displacement by two-dimensional analysis. Deformations are compared in Figure 11 for cases no-tension 1 and no-tension 2. Clear separation is observed between the caissons at the corner, which is the reason why large displacement is obtained in the no-tension 2 analysis. In this analysis, separation of soil element at the corner cannot be modeled, but it is considered as separation between caissons as well as soil elements.

It is emphasized that no joint or interface element is used in the two-dimensional analysis. Therefore, smaller displacement observed in no-tension 2 analysis is characteristics observed in three-dimensional analysis. It is also focused that two-dimensional analysis that does not use interface element shows the same displacement with three-dimensional analysis that uses interface element. Shear deformation is the most important as discussed in ALID (Yasuda et al, 1999) in the two-dimensional analysis and it is considered in the analysis. On the other hand, consideration of shear deformation is not sufficient in the three-dimensional analysis; tensile behavior must be taken into account.

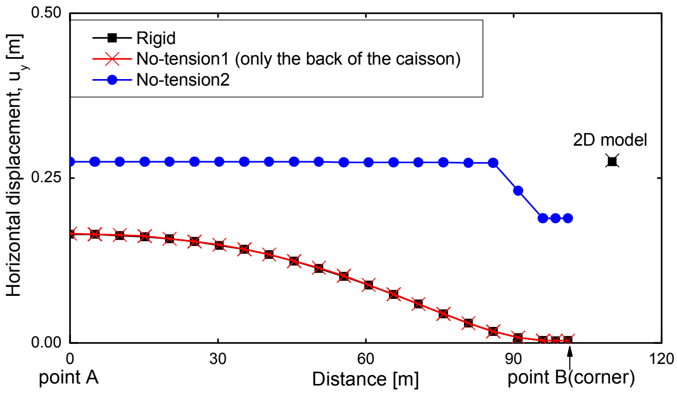
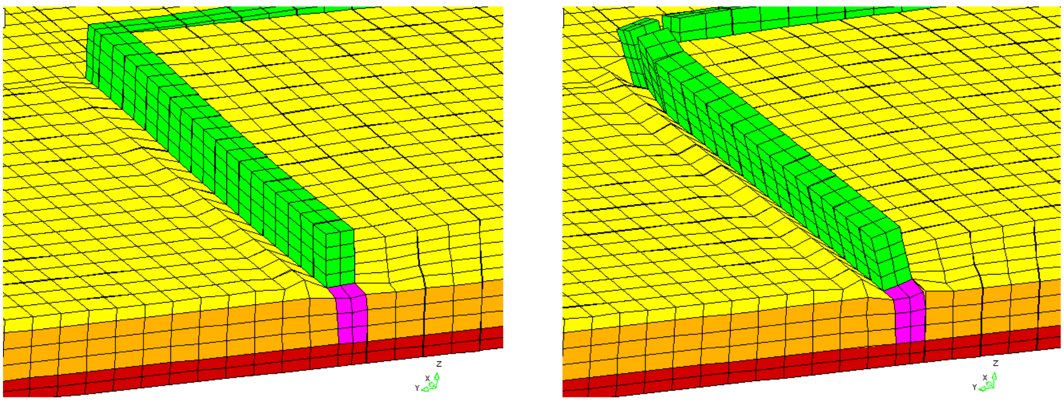


Figure 10 Comparison of displacements



a) No-tension 1 b) No-tension 2

Figure 11 Comparison of displacement, where displacement is enlarged 20 times.

5. CONCLUSION

Three-dimensional analysis is carried out and accuracy of it is examined. Since ordinary finite element analysis underestimated displacement significantly not only at the corner but also along the side where two-dimensional analysis has been valid. It means consideration of shear deformation is sufficient in two-dimensional analysis, where as tensile behavior is also important in three-dimensional analysis because volume of soil element increases if flow occurred in two directions. Instead of considering tensile behavior, use of joint or interface element is considered in this paper. Interface element or joint element between caisson and adjacent soil element, and between caissons are not enough in expressing realistic displacement, because volume increase of soil element is not considered, and consideration of separation between soil elements is necessary. It is noted that this kind of separation is not necessary to be considered in two-dimensional analysis, but necessary in three-dimensional analysis.

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