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# Liquefaction Countermeasure Utilizing Overburden Pressure from Mat Foundation and Grid Underground Wall

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## ABSTRACT

A new methodology of liquefaction countermeasure which utilizes both the effect of the overburden pressure from mat foundations and the effect of shear strain constraint by a grid underground wall is presented. The liquefaction suppression effect of the countermeasure is examined through dynamic centrifuge tests. The test results confirm that combination of the overburden pressure from mat foundations and the grid underground wall effectively suppresses liquefaction. This tendency is dominant when the contact pressure of the foundation is large and the grid spacing is small. Moreover dynamic numerical simulations using an effective stress FEM are conducted and the efficiency of the numerical technique as a designing tool is verified.

## Introduction

The grid underground wall which constraints shear strain of soil is widely used as an effective liquefaction countermeasure for buildings in Japan. On the other hand, the liquefaction resistance of soil just under a building which stands on its mat foundation should be higher than the original resistance because of the larger overburden pressure. Authors conceived an idea to combine this overburden pressure effect with the shear constraint effect of the grid underground wall. The idea was verified through a series of centrifuge testing (Funahara et al. (2012)). In this paper, numerical simulations conducted by using an effective stress FEM, which are expected to be an evaluation tool, are additionally presented.

## Liquefaction Suppression Principle Studied in This Research

The vertical load of a building which stands on a grid underground wall with a mat foundation is primarily carried by the relatively rigid grid underground wall rather than the soft soil contained within the grid. In this study, some softer material or void is expected to be placed on the grid underground wall, in order to transmit a majority of the building vertical load to the soil beneath the structure rather than to the underground wall (Figure 1). Since the building load is transmitted to the inside ground, the liquefaction resistance of the inside ground is expected to increase. Additionally the grid underground wall prevents the inside ground from shear-deforming. The combination of these two effects (i.e. the overburden pressure effect and the grid underground wall effect) is postulated to be utilized as a new liquefaction countermeasure. The grid underground wall is also expected to prevent the structure from settling due to the lateral

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movement of the underlying ground succeeding the liquefaction of the surrounding ground. Moreover the grid underground wall would prevent the excess pore water pressure in the surrounding liquefied ground from being transmitted to the underlying ground just under the foundation.

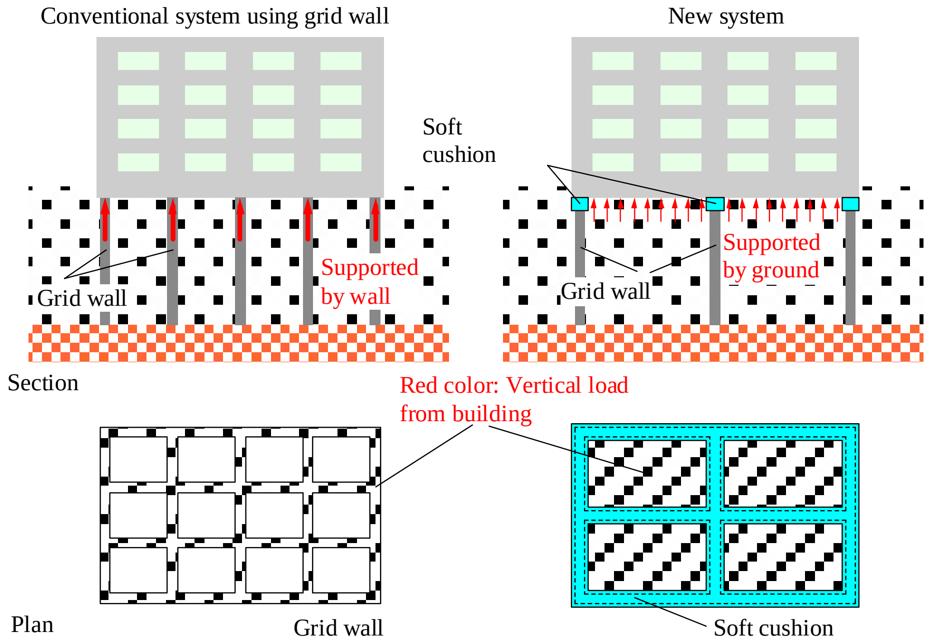
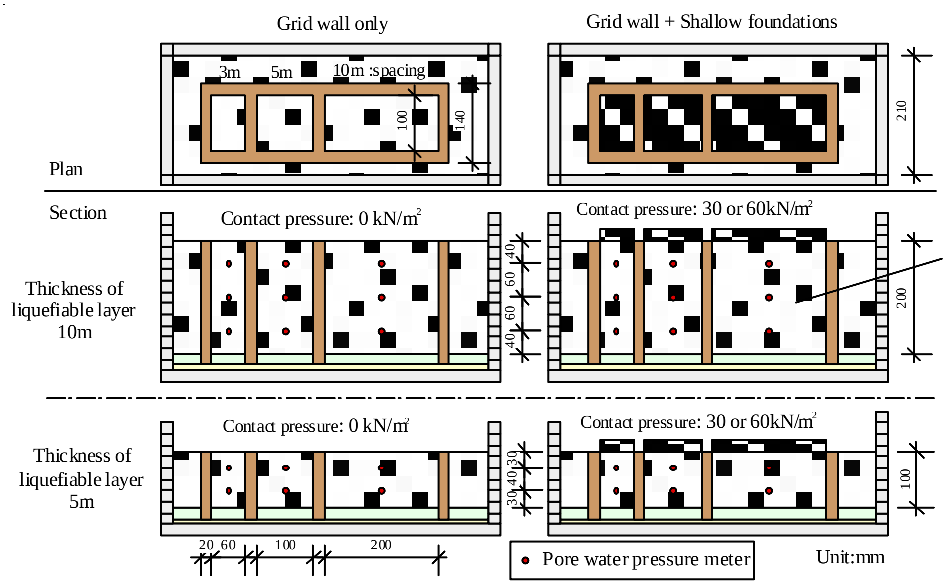



Figure 1. Conventional countermeasure and proposed new system

## Dynamic Centrifuge Testing on the Liquefaction Suppression Effects

### *Test model and measurements*

In order to examine the liquefaction suppression effects mentioned above, dynamic centrifuge tests were conducted. Figure 2 shows the experimental models used in the centrifuge tests and the sensor distributions. A saturated sand model and a grid underground wall model made with acrylic are set in a laminar shear box. Solid plates are placed on the surfaces of inside grounds of the grid wall to model mat foundations. The thickness of each plate is designed to apply the desired contact pressure to each grid zone, and the length of each plate edge is smaller than the length of each grid edge by 1 mm. The ground model is made with Toyoura sand and is saturated using silicone oil. The targeted relative density of the soil is 60 %. The important parameters of the tests are the contact pressures of the mat foundations, the spacing of the grid underground wall, and the thickness of the liquefiable ground. The key measurements are the excess pore water pressures. All of the physical quantities presented in the following parts are expressed in the prototype scale. The employed contact pressures are 0, 30, 60 kN/m$^2$ and the employed grid wall spacings are 3, 5, 10 m. The thicknesses of the ground are 5, 10 m. Seismic motion is applied using a shaking table in the centrifugal field of 50 g. The seismic motion is a synthetic wave called ' Rinkai wave ' and is scaled about 40% of the original one (Figure 3).




| Thickness of the ground | Model | Contact pressure (kN/m$^2$) |
|---|---|---|
| 10m | No.1 | 0 |
| | No.2 | 60 |
| | | (30) |
| 5m | No.1 | 60 |
| | No.2 | 30 |
| | | (0) |

Figure 2. Physical models for centrifuge testing

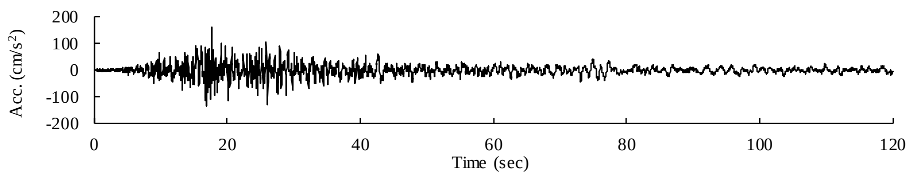



Figure 3. Input seismic motion for shaking table

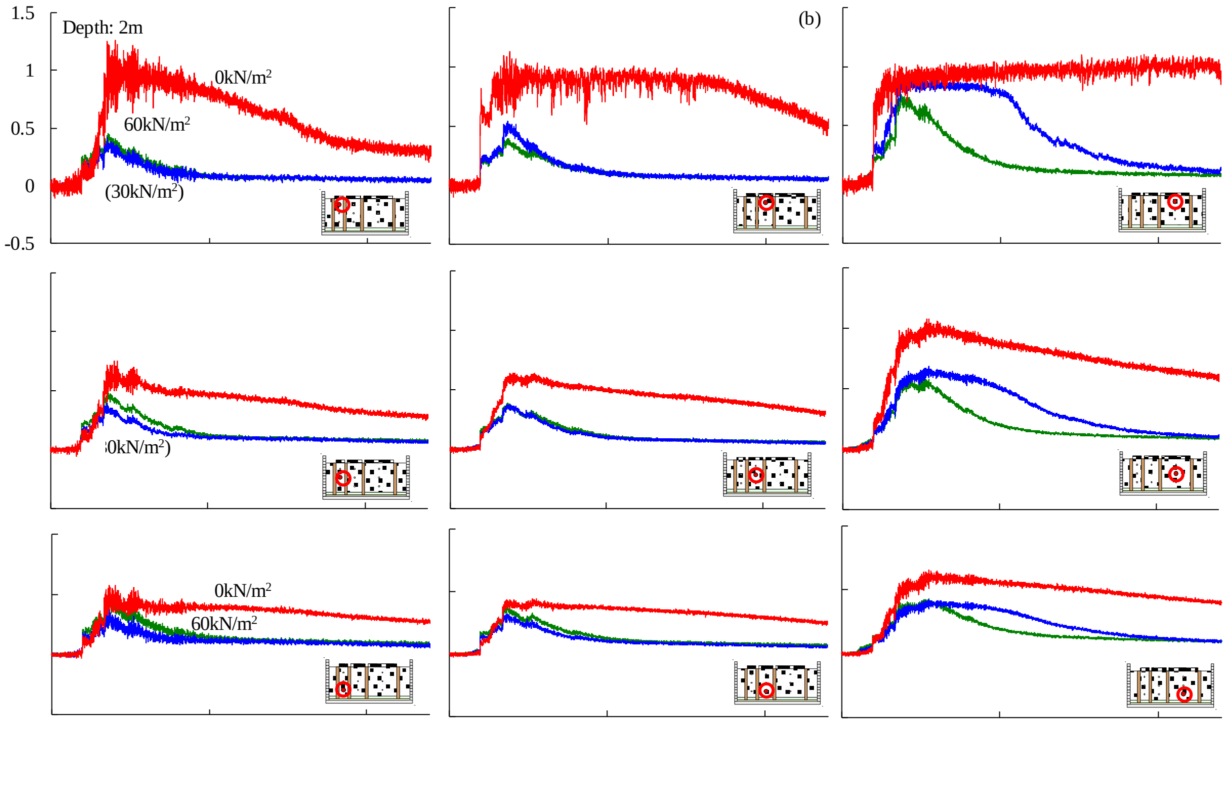
### *Excess pore water pressure ratio as an index of liquefaction extent*

The excess pore water pressure ratio is employed as an index of the liquefaction degree. The excess pore water pressure ratio is calculated by dividing the excess pore water pressure by the initial effective overburden pressure. The initial effective overburden pressure is estimated considering the self-load of the soil itself and the contact pressure at the ground surface. Figure 4 presents the time histories of the excess pore water pressure ratios. The upper figures (A) are for the ground thickness of 10 m, and the lower figures (B) are for the ground thickness of 5 m. The pore water pressure meters are set at three levels in the 10m ground model and set at two levels in the 5 m ground model as shown in Figure 2. In each graph, data for three different contact pressures are compared. Note that the 10m ground model with 30 kN/m$^2$ contact pressure and the 5m ground model with 0 kN/m$^2$ contact pressure are not virgin but have experiences of one-time excitation with the contact pressure of 60 and 30kN/m$^2$ respectively and those irregular cases are indicated using parentheses in Figure 4 (Also see the chart in Figure 2).

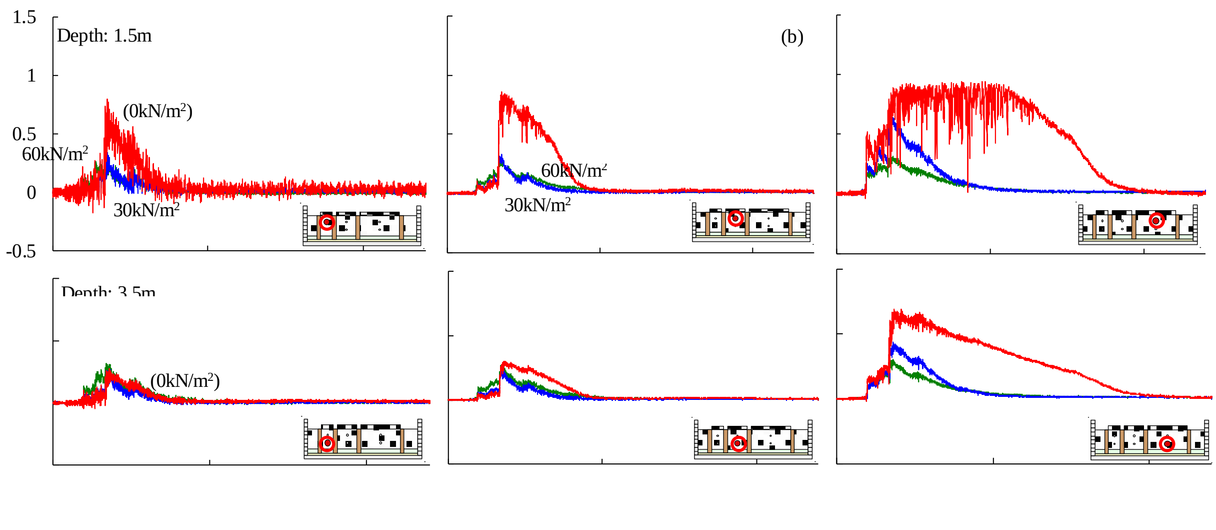
### *Effect of contact pressure of mat foundation*

Comparing three lines in each graph of Figure 4, the excess pore water pressure ratios under the mat foundations tend to be smaller than those without mat foundations. This suggests that the overburden pressure from mat foundations could suppress the liquefaction occurrence.

Especially in the grid of 10 m spacing (right hand graphs in Figure 4), the tendency that the larger the contact pressure, the larger the liquefaction suppression effect, could be recognized.




(A) Soil thickness: 10 m




(B) Soil thickness: 5 m

Figure 4. Excess pore water pressure ratio observed in the centrifuge tests

### *Effect of grid spacing*

Regarding the effect of the grid spacing on the liquefaction extent, there is a tendency that the smaller spacing (left hand graphs in Figure 4) suppresses the liquefaction more compared to the larger spacing (right hand graphs in Figure 4). The ground in the grid of 3 m and 5 m spacing are not liquefied due to the relatively small contact pressure of 30 kN/m$^2$, but the same contact pressure does not prevent the liquefaction in the 10 m thick ground in the grid of 10 m spacing. This suggests that the larger contact pressure might be required to suppress liquefaction for larger grid spacing.

### *Effect of ground thickness*

The pore water pressure ratios in the 10 m thickness ground (Figure 4A) are larger than those in the 5 m thickness ground (Figure 4B) in this testing. Therefore it might be suggested that the larger contact pressure might be necessary to suppress the liquefaction for the thicker ground. But the thickness of the ground generally affects the ground response itself. So this might not be always true.

### *Effect of distance from the bottom of foundation*

Even in the case that the liquefaction at the deeper depth is suppressed without the mat foundation, it can be recognized that the liquefaction at the shallower depth could not be suppressed only by the same spacing grid. On the other hand, for such a shallow depth, it can be pointed out that a small contact pressure like 30 kN/m$^2$ could suppress liquefaction effectively. At a shallow depth, it can be said that the effect of the contact pressure from the building is relatively large because the initial effective pressure due to the soil weight is small.

## Numerical Simulations Using Effective Stress FEM

### *Numerical model*

In order to verify the applicability of a numerical technique as a designing tool of the liquefaction countermeasure being proposed in this study, simulation analyses of the centrifuge tests were conducted. An analytical tool which is employed is an effective stress FEM code "DIANA-J2" which has "Stress-Density Model (Cubrinovski et al. (1998a))" as a constitutive model for saturated sand. Figure 5 shows the schematic view of the numerical model for the physical model in the centrifuge test. The numerical model is 2-Dimensional and both the soil and the underground wall are modeled using plane strain elements. The employed parameters of Stress-Density Model (Cubrinovski et al. (1998b)) and its liquefaction strength curve for the effective confining stress of 100kN/m$^2$ are shown in Figure 6. This model is designed to express the stress-dependent behavior of sand reasonably. Therefore it is expected that the effect of the increased overburden pressure due to the mat foundations could be reasonably reproduced. The targeted in-situ liquefaction strength is evaluated using the triaxial liquefaction strength 0.13 at the cyclic number of 15 (Toki et al. (1986)) and assuming the coefficient of earth pressure at rest $K_0$=0.5. When the contact pressure of the mat foundation is considered, a rigid beam is placed on the soil surface and the corresponding vertical load is applied on it to model the contact pressure. The plane strain elements for underground wall is given elastic properties of acrylic (i.e. Young's modulus: 3350MN/$m^2$, poison’s ratio: 0.35, density: 1.16*$10^3$kg/$m^3$).

The fixed boundary condition is applied at the bottom and the periodic boundary condition is applied on side boundaries. The plane strain elements for the liquefiable soil in the grid wall and the plane strain elements for the elastic in-plane wall have the same coordinates but consist of different nodes except for the side edges of the wall. The acceleration of the shaking table recorded in the centrifuge testing is used as an input motion for the dynamic simulation.

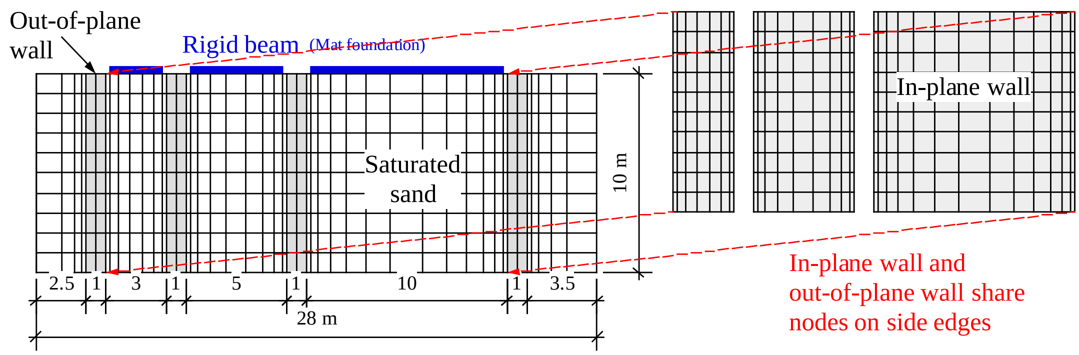



Figure 5. Numerical model

| Elastic parameters | | | Void ratio | Dilatancy parameters | | |
|---|---|---|---|---|---|---|
| A | ν | n | e | M | $\mu_0$ | Sc |
| 150 | 0.2 | 0.6 | 0.7538 | 0.607 | 0.22 | 0.000419-0.001917 |

| Parameters for schelton curve | | | | | | |
|---|---|---|---|---|---|---|
| $\alpha_1$ | $\beta_1$ | $\alpha_2$ | $\beta_2$ | $\alpha_3$ | $\beta_3$ | f |
| 0.58 | 0.023 | 78.7 | 16.5 | 230.0 | 65.5 | 4.0 |

| Quasi steady state line | | | | | | | |
|---|---|---|---|---|---|---|---|
| $e_0$ | $e_1$ | $e_{10}$ | $e_{30}$ | $e_{50}$ | $e_{100}$ | $e_{200}$ | $e_{400}$ |
| 0.895 | 0.878 | 0.877 | 0.873 | 0.870 | 0.860 | 0.850 | 0.833 |

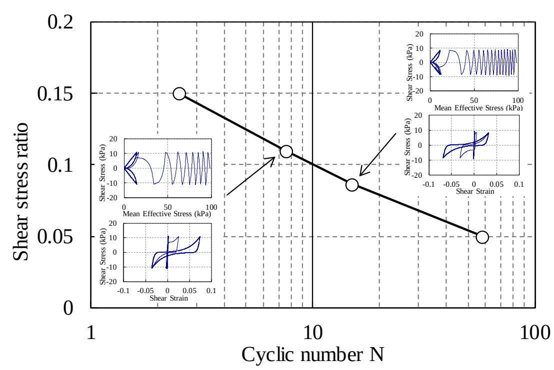
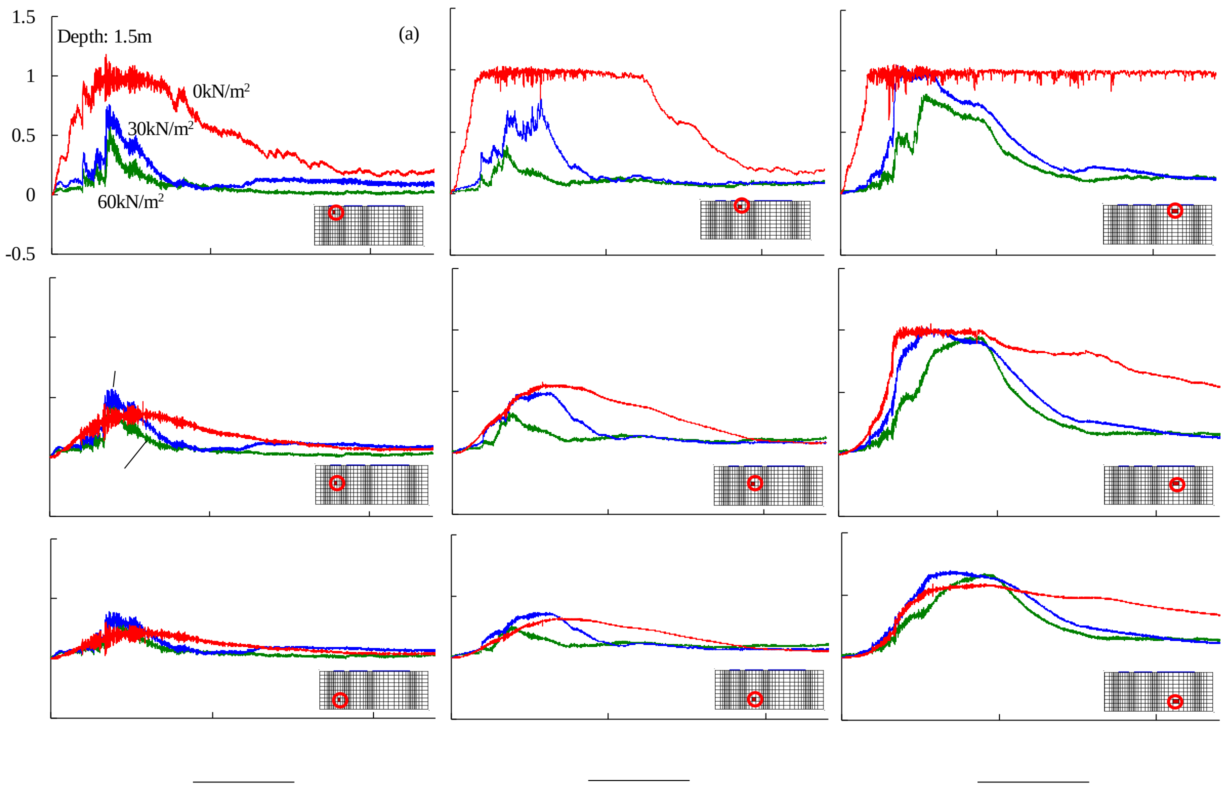



Figure 6. Model parameters and liquefaction strength of the constitutive model

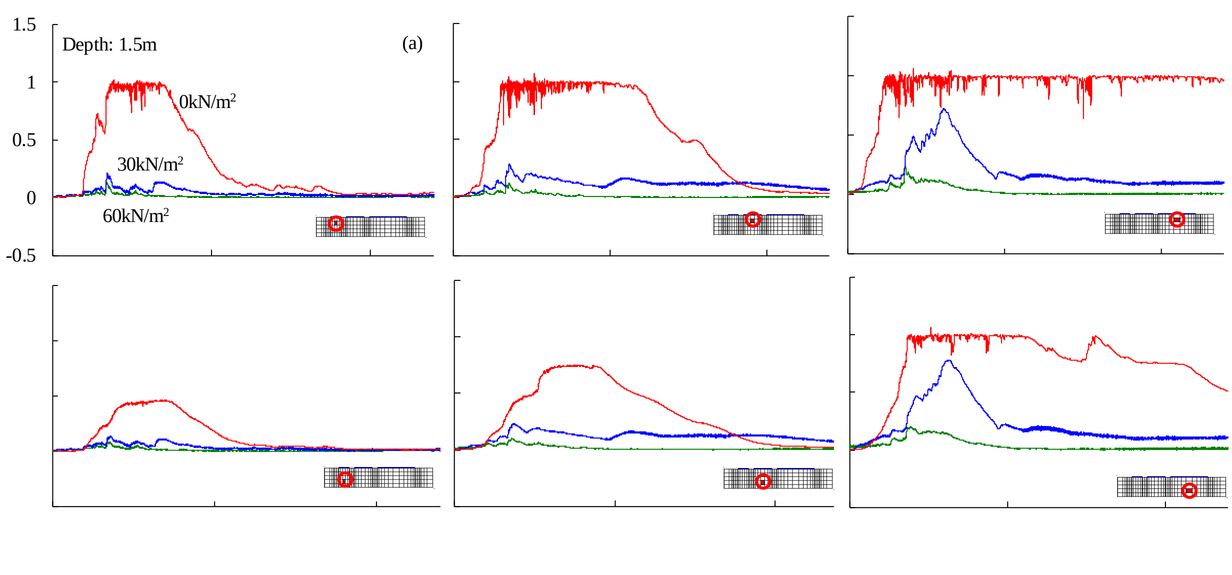
### *Simulation results*

The excess pore water pressure ratio is calculated dividing the excess pore water pressure in the simulation by the initial effective overburden pressure. The time histories of the excess pore water pressure ratio are presented in Figure 7.

The overall tendencies which could be recognized in the simulation results are consistent with the centrifuge test results shown in Figure 4. As mentioned regarding the centrifuge test results, the contact pressure from the mat foundation suppresses the excess pore water pressure ratio (for example, see (a)-(b) in Figure 7A, and (a)-(f) in Figure 7B). Additionally the larger contact pressure and the smaller grid spacing are more effective to suppress the liquefaction. In the simulation, there is no effect of the one-time excitation experience like in the testing. Therefore the difference between the contact pressure 30kN/$m^2$ and 60kN/$m^2$ for the 10m ground model is clearer than the centrifuge testing (for example, see Figure (a), (b) in Figure 4A and 7A).




(A) Soil thickness: 10 m




(B) Soil thickness: 5 m

Figure 7. Excess pore water pressure ratio calculated in the numerical simulation

The contours of the excess pore water pressure ratio at the time of 35 second for the 10m ground model and at the time of 36 second for the 5m ground model are shown in Figure 8. The red color indicates that the excess pore water pressure ratio is 1.0 and the soil is liquefied.

The same tendencies mentioned above could be recognized here also. The larger contact pressure and the smaller grid spacing are more effective to suppress the liquefaction (for example, see (a) -(c) in Figure 8). As is the case in the centrifuge testing, the thicker ground tends to easily liquefy if the contact pressure from the mat foundation is the same (see (b) and (e), or (c) and (f) in Figure 8). A cause of this difference would be the difference in the amplification characteristics of the ground itself.

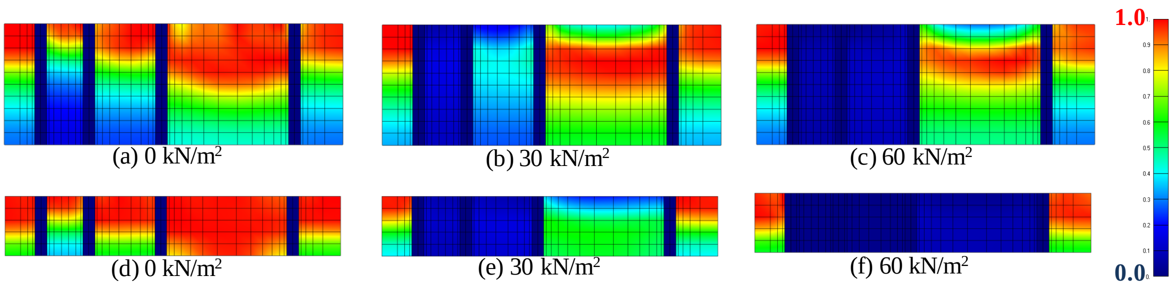



Figure 8. Contour of excess pore water pressure ratio

## Conclusions

Based on the centrifuge testing and the effective stress analyses on the liquefaction countermeasure utilizing the grid underground wall and the effect of the contact pressure of the mat foundation, the following results were found.

- The liquefaction extent just under the mat foundations is suppressed due to the effect of the contact pressure of the foundations.
- This tendency is dominant if the contact pressure is larger and the grid spacing is smaller.
- The employed effective stress FEM program successfully simulates the liquefaction extent observed in the centrifuge testing. This supports the ability of the program as an evaluation tool of the liquefaction countermeasure being proposed in this study.

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