Effectiveness of Simple Method Determining Space for Grid-form Deep Cement Mixing Walls

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Summary

In a previous paper, the authors proposed a method to evaluate the shear stress of the soil surrounded by cement mixing walls. To improve the reliability of the simple calculation method that the authors proposed, a seismic response analysis was conducted to modify the parameters – grid space, shear modulus of the improved soil, and the length. Based on the analysis, three functions that composed the expression were reviewed. The reviewed method was evaluated for the maximum shear stress of the soils based on the seismic response analysis.

Keywords: liquefaction, grid-form deep cement mixing walls, grid space

1 INTRODUCTION

Grid-form deep cement mixing walls is a method in which the ground is improved in a planar and a grid-like manner using a cement-based solidification material and liquefaction is prevented by suppressing the deformation of the ground using underground walls, as shown in Figure 1. When using this method as a countermeasure to liquefaction, grid spacing needs to be determined based on anticipated seismic motion and ground conditions. The authors proposed a simple calculation method for evaluating shear stress during an earthquake of an unimproved ground surrounded by a grid wall (ground inside the grid) and had used the method for designing the grid-form deep cement mixing walls [1]. Correction coefficients that constitute this method were revised to enable the use of this method for seismic motions with a large magnitude, such as the Tohoku earthquake[2].

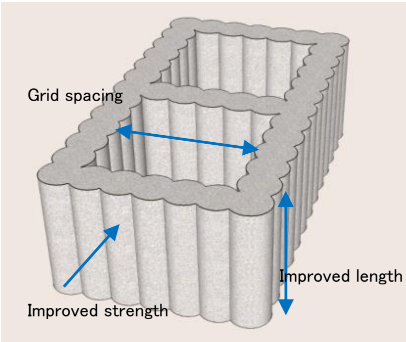

Fig. 1 Grid-form deep cement mixing walls method

This report introduces a revised simple calculation method considering increase in strength, evaluates the simple method by conducting a seismic response analysis for a case in which the grid-form deep cement mixing walls were utilized, and reports on the analysis of the effectiveness of the revised method.

2 Overview of the simple calculation method[1), 2)]

2.1 Composition of the simple calculation method

Factors such as grid spacing, strength, and length should be determined to design the grid-form deep cement mixing wall for use as a measure against liquefaction of the ground. To decide these specifications based on seismic motions and ground conditions, seismic response analysis through approaches such as FEM analysis capable of expressing the effects of constraints on the ground by improved walls are generally used. The authors performed a seismic response analysis (equivalent linear analysis) by super-FLUSH with a quasi-three-dimensional model (shown in Figure 2) using grid spacing, shear modulus of the improved soils and improved length in Reference 1, and proposed equation (1) for a straightforward evaluation of the shear stress

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at the central part of the ground inside the grid during an earthquake.

$$\left(\frac{\tau_d}{\sigma_z'}\right)_{Grid} = \gamma_n \frac{\alpha_{max}}{g} \cdot \frac{\sigma_z}{\sigma_z'} \cdot \gamma_d' \cdot FL(L) \cdot FG(G) \cdot FH(H) \qquad (1)$$

In the above equation, $(\tau_d/\sigma_z')_{Grid}$ represents shear stress ratio at the central area of the ground inside the grid, γ_n=0.1(M-1), M is the magnitude, α_{max} is the maximum acceleration of the ground surface, g is the acceleration due to gravity, σ_z is the total stress, σ_z' is the effective stress, γ_d' is the reduction coefficient in the depth direction, FL (*L*) is the impact of grid spacing *L*, FG(*G*) is the impact of shear modulus, and FH(*H*) is the correction coefficient for the impact of improved length.

Additionally, the range of application of improved length was expanded from 15m to 20m in Reference 2, observed waves from the Tohoku earthquake was added to seismic motions for considerations, and correction coefficients for equation (1) were revised by performing a seismic response analysis with a defined target maximum acceleration of the ground surface. Please refer references (1) and (2) for details on seismic response analysis.

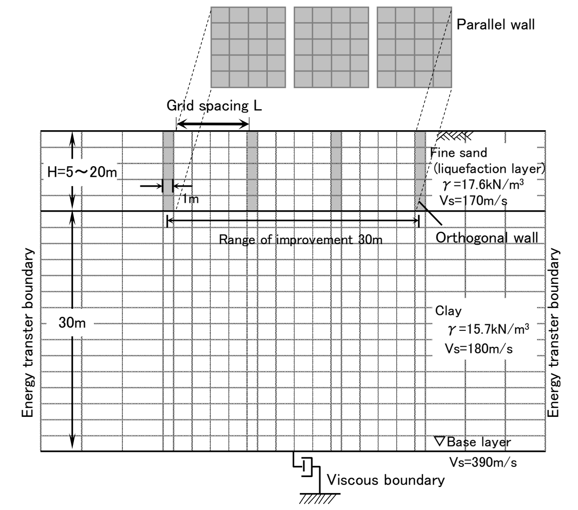


Fig. 2 Analysis model

2.2 Revision of correction coefficient

The analysis cases performed to revise correction coefficient are shown in Table 1. Seismic response analysis was performed using improved length, grid spacing, and shear modulus of the improved soils as parameters, and the maximum shear stress of the ground inside the grid was calculated. Input for modeling the seismic motion were, the NS component of a record at GL-32m from a vertical array at Port Island during the 1995 Southern Hyogo Earthquake (i.e. PI waves), and the waves at engineering bedrock of the Yumenoshima during the 2011 Tohoku earthquake (Yumenoshima wave). The target value of the maximum acceleration at the ground surface in the analysis, at an unimproved ground model where H=5m, was 3.5m/s^2 for PI waves, and 2.0m/s^2 for Yumenoshima waves. Upon evaluating the results of the analysis using equation (1), α_{max} was assumed to be the maximum acceleration at the surface of an unimproved ground (Table 2). The reduction coefficient γ_d' that best simulates the relationship between maximum shear stress τ_{max} and depth of the analysis result was also calculated. Furthermore, the correction coefficients F(*L*), F(*G*), and F(*H*) for each analysis case were calculated. Plots of correction coefficients obtained per seismic motion and approximation of the average are shown in Figure 3 and equations (2)～(5).

Table 1 Analysis case

Thickness of the fine sand layer *H* (m) (Improved length)	Grid spacing *L* (m) (inner measurements)	Shear modulus of the improved soils *G* (N/mm^2)
5	2.75,4,9,14,29	700
10	4, 9, 14	700
15	9, 14, 29	700
20	9, 14, 29	700 For L=9 and 29m only, add *G*=200,350,1400,2100

Table 2 Input seismic motions and response by the unimproved ground

Seismic waves	Maximum input acceleration (m/s^2)	Max. acceleration at the ground (m/s^2)			
		H=5m	*H*=10m	*H*=15m	*H*=20m
P1 wave	3.62	3.5	3.86	3.39	2.68
Yumenoshima wave	1.52	1.89	1.7	1.61	1.44

$$FL(L) = 0.29 \log_e(L) - 0.12 \qquad 4 \leqq L(\mathrm{m}) \leqq 20 \qquad (2)$$

$$FG(G) = -0.45 \log_e(G) + 3.94 \quad (L \leqq 9\mathrm{m})$$

$$= -0.33 \log_e(G) + 3.16 \quad (9\mathrm{m} < L \leqq 19\mathrm{m})$$

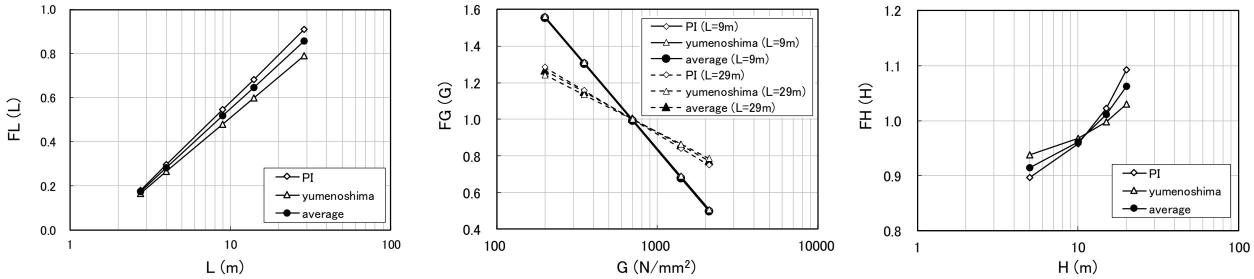
$$= -0.21 \log_e(G) + 2.38 \quad (19\mathrm{m} < L \leqq 20\mathrm{m})$$

$$350 \leqq G(\mathrm{N/mm^2}) \leqq 1400 \qquad (3)$$

$$FH(H) = 0.87e^{0.01H} \qquad H(\mathrm{m}) \leqq 20 \qquad (4)$$

$$\gamma_d' = 1 - 0.026z \quad z(\mathrm{m}) \qquad (5)$$

τ_{max} obtained from the analysis and τ_{max} obtained from equation (1) using the correction coefficient (average) from Figure 3,

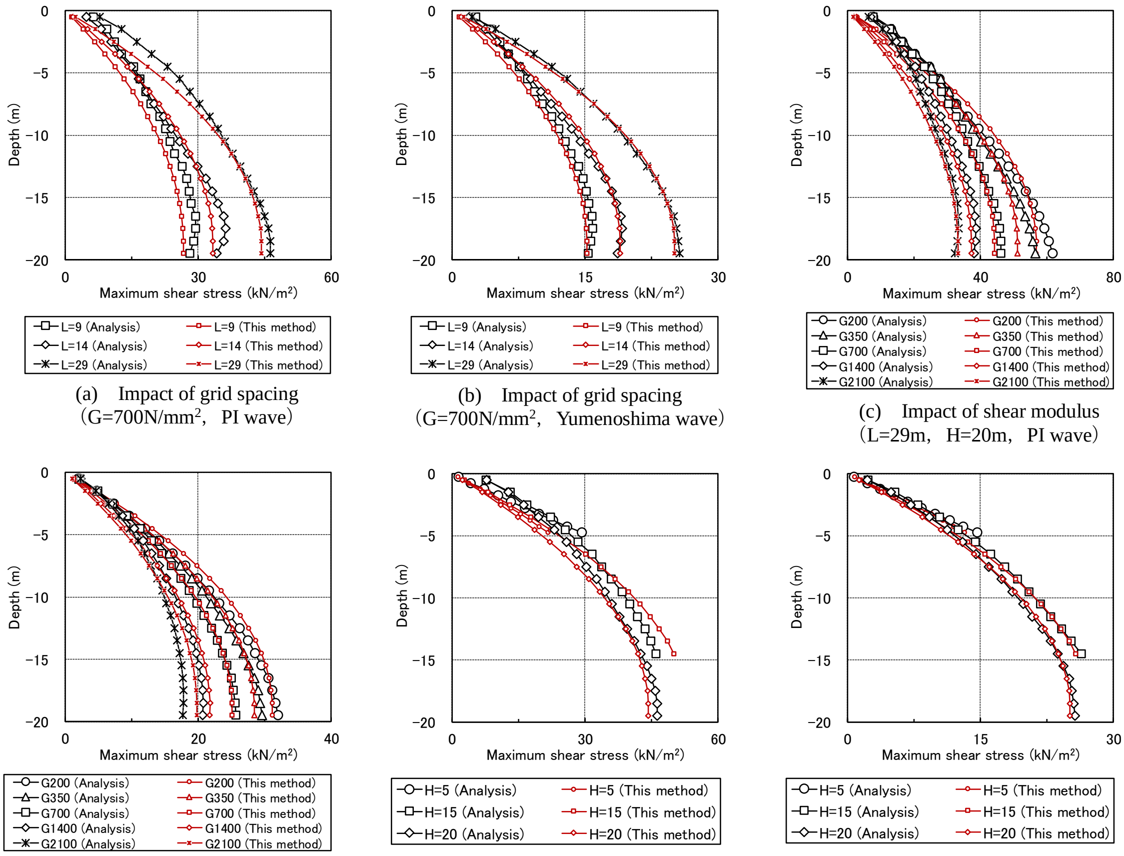


(a) Correction coefficient for grid spacing

(b) Correction coefficient for shear modulus of the improved soils

(c) Correction coefficient for improved length

Fig. 3 Correction coefficient of the simple calculation method



(a) Impact of grid spacing (G=700N/mm², PI wave)

(b) Impact of grid spacing (G=700N/mm², Yumenoshima wave)

(c) Impact of shear modulus (L=29m, H=20m, PI wave)

(d) Impact of shear modulus (L=29m, H=20m, Yumenoshima wave)

(e) Impact of improved length (L=29m, G=700N/mm², PI wave)

(f) Impact of improved length (L=29m, G=700N/mm², Yumenoshima wave)

Fig. 4 Comparison of the maximum shear stress of ground inside the grid calculated by the analysis and the simple method

are combined and shown in figure 4. The graphs in figure 4 show that this method of evaluation can generally evaluate changes in shear stress of the ground inside the grid due to the differences in grid spacing, modulus of the improved soils, improved length, and seismic waves.

2.3 Equation for determining the grid spacing

If the shear stress inside the grid can be evaluated by equation (1), then FL values of the ground inside the grid can be calculated by the following equation.

$$FL=\left(\frac{\tau_l}{\sigma_z'}\right) / \left(\frac{\tau_d}{\sigma_z'}\right)_{Grid} \qquad (6)$$

Where, $(\tau l/\sigma_z')$ is the liquefaction resistance ratio, which was calculated from N value based on the "Recommendations for the design of building foundations"[3).

Grid spacing L needed to prevent liquefaction can be calculated by the following equation, where equation (1) is substituted into equation (6) and solved for the L in correction coefficient F(L):

$$L=\exp\left[\frac{(\tau_1/\sigma_z')/\{FL_d\cdot\gamma_n\cdot(\alpha_{max}/g)\cdot(\sigma_z/\sigma_z')\cdot\gamma_d'\cdot F(G)\cdot F(H)\}+0.12}{0.29}\right] \qquad (7)$$

Where, FL_d is the design safety ratio. If equation (7) is used, grid spacing can be determined such that the FL values of the ground inside the grid is at or above 1.0.

Since FG(G) is influenced by the grid spacing as shown in Figure 3(b), equation (3) was employed for each range of grid spacing.

3 Verification of the simple calculation method through test cases

In order to verify the usability of the proposed simple calculation method, evaluation by the method and the result from the seismic response analysis were compared for several cases in which grid-form deep cement mixing walls approach was used. Table 3 shows the list of cases.

Table 3 Specification of the grid-form deep cement mixing walls in test cases

No.	improved soil condition							maximum acceleration of surface on unimproved ground (m/s²)
	maximum grid space width (m)	maximum grid space length (m)	width/length	improved length (m)	improved depth (GL-m)	shear modulus (N/mm²)	design strength (N/mm²)	
1	14.6	15.5	0.94	14	1.0~14.0	700	1.5	2.93
2	13.25	14.5	0.91	11.85	4.15~16.0	700	1.5	2.27
3	14.5	14	1.04	7	3.0~10.0	700	1.5	2.98
4	11.2	7.7	1.45	5.45	3.05~8.5	700	1.5	3.32
5	13.4	9.8	1.37	9.3	1.4~10.7	800	1.8	2.78
6	9.75	12.25	0.80	18	1.4~18.0	700	1.5	2.87

In the seismic response analysis, the part with the range in which the grid spacing is the greatest was treated as the analyzed cross section, and seismic response for the range designated on both sides of the width equivalent of the building width, which is the range of improvement, was evaluated via a quasi-three-dimensional equivalent linear analysis (super-FLUSH). An example of the analysis model is shown in Figure 5. The part drilled due to the construction of the building was treated as a model with the ground element removed. The ground model was developed for each case based on the result of PS well logging up to engineering bedrock of Vs＝400 m/s, and seismic response analysis was performed using the design spectrum compatible time histories. Shear modulus of the improved soils was defined based on the design strength. Maximum acceleration of the ground surface for unimproved ground in cases where design spectrum compatible time histories are used for engineering bedrock without amplitude adjustments is shown in the table (i.e. design input). The response of an unimproved ground was defined as the response at the outermost area of the range subjected to the analysis, as shown in Figure 5. Application cases were selected such that the response acceleration at the ground surface was less than 3.5m/s² against the design input. Using same seismic waves, another case in which the response acceleration of the ground was set as 2.0m/s² by adjusting the input amplitude (i.e. 2.0m/s² at ground surface) was also considered.

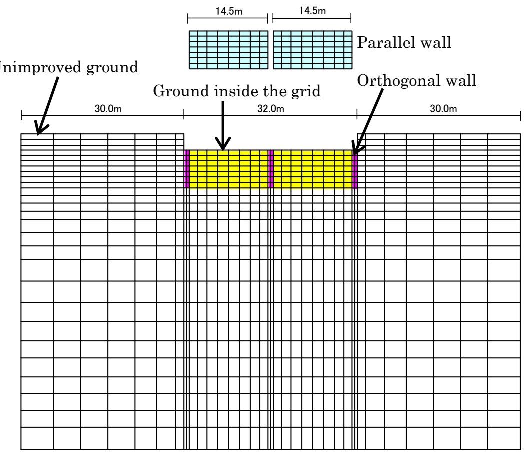


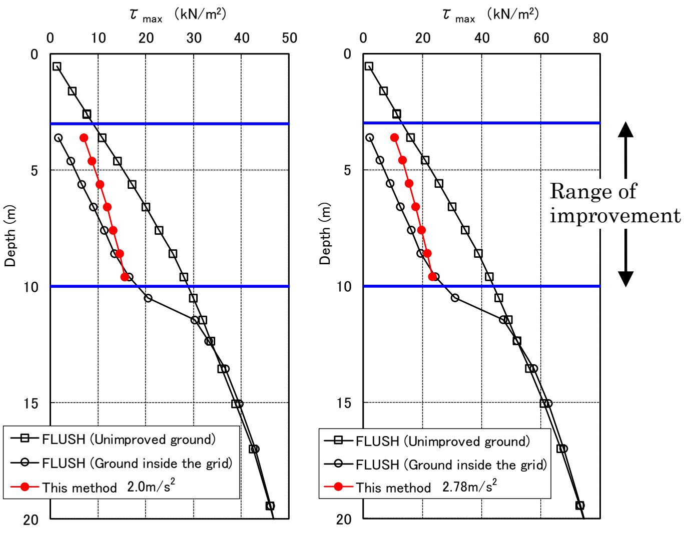
Fig. 5 Analysis model example (Case No. 3)

In an evaluation by the simple method, shear stress was calculated as a grid spacing where rectangular grid form is converted to a square with an equivalent area. The maximum acceleration from Table 3 and 2.0m/s² were used at the ground surface upon calculating the maximum shear stress in the ground inside the grid.

Figure 6 is a comparison of maximum shear stress τ_{max} of the ground inside the grid calculated by seismic response analysis and simple calculation method in Case No. 3. In the analysis, τ_{max} of the ground inside the grid is smaller compared to the unimproved ground at the depth-of-improvement range. τ_{max} by the simple calculation method tends to be larger at a shallower part compared to the analysis for both design input and 2.0m/s² at the ground surface. This is likely impacted by the difference in the evaluation of the stress at the shallow ground, where the ground element of the drilled range from building construction is removed in the calculation by seismic response analysis, while the simple method calculates from the ground surface.

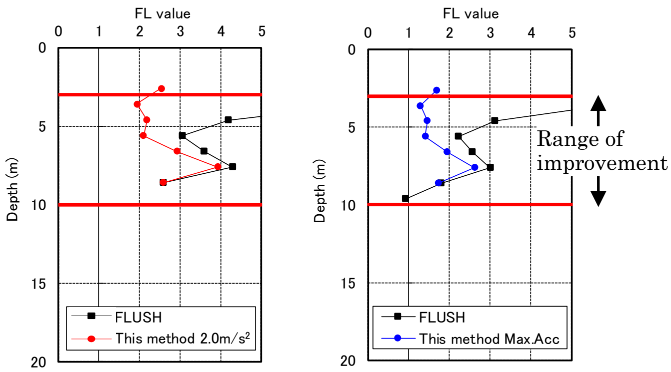
Figure 7 is a comparison of FL values for the ground inside the grid calculated by the simple calculation method and seismic response analysis. FL values calculated by the simple method are smaller than the result of the analysis at the depth-of-improvement range, and this evaluation is on the safe side.

Figures 8 and 9 compare FL values by the simple calculation method and the analysis at the depth-of-improvement in the case considered in this study. Figure 8 is for the case for the ground surface at 2.0m/s^2, while Figure 9 is the case using a design input. Maximum acceleration at the ground surface in the simple calculation method to be compared with design input is shown in Table 3. In the range less than GL-5m in Figures 8(a) and 9(a), FL values by the simple calculation method can be significantly smaller than the value by the analysis. This is due to the difference, in which the seismic response analysis is performed with the ground element removed from the calculation, while the simple calculation method is calculated from the ground surface. Whereas, FL values by the simple calculation method are slightly smaller for GL-5～10m and GL-10～20m ranges compared to the values by the analysis. This fact underscores that the simple calculation method results in an evaluation on the safe side as a way to determine grid spacing for grid-form deep cement mixing walls against each level of seismic motion.



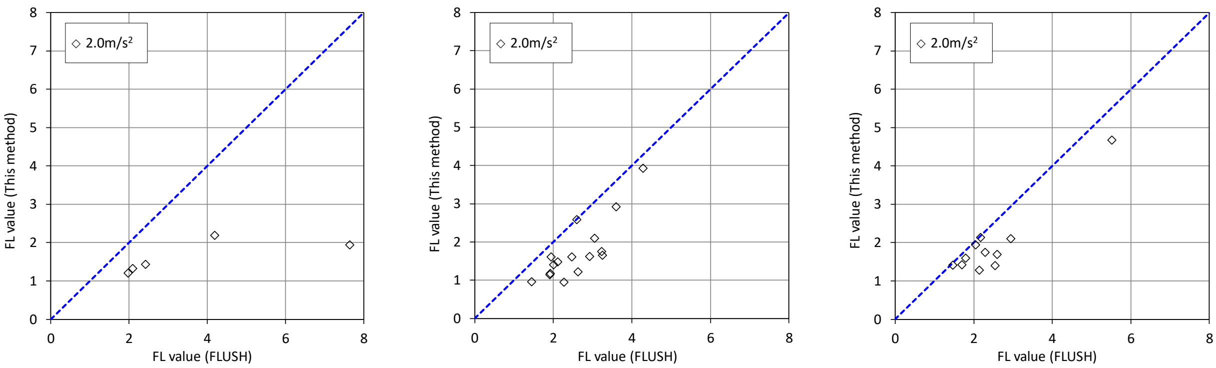
(a) Ground surface 200cm/s^2 (b) Simulated input

Fig. 6 Maximum shear stress (Case 3, drilling depth 3.0m)



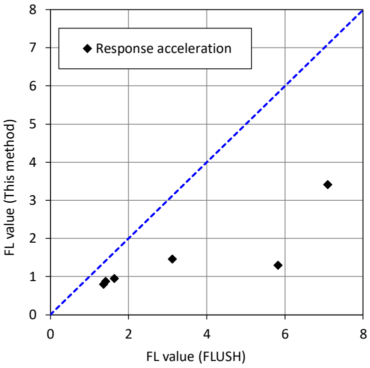
(a) Ground surface 200cm/s^2 (b) Simulated input

Fig. 7 FL value inside the grid

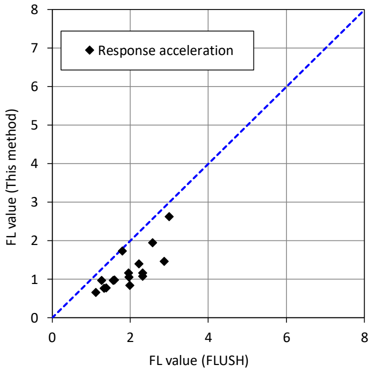


(a) GL-5m or less (b) GL-5m～10m (c) GL-10m～20m

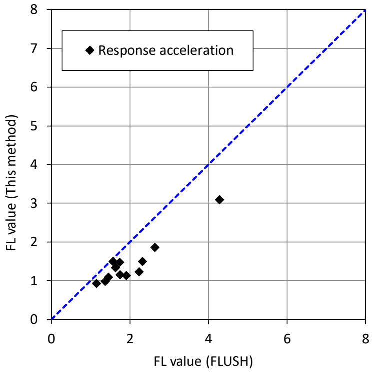
Fig. 8 Comparison of FL values (α_{max}=2.0m/s^2)



(a)　GL-5m or less



(b)　GL-5m～10m



(c)　GL-10m～20m

Fig. 9　Comparison of FL values (α_{max}＝response acceleration)

4. Conclusions

This report introduced a revised simple calculation method for determining a grid spacing in a grid-form deep cement mixing wall utilized to prevent liquefaction of the ground and verified its usability through an application case. In the range where response acceleration at the ground surface is less than 3.5m/s^2, FL values calculated by the simple calculation method were slightly smaller than the result obtained by the seismic response analysis.

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