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FEM analysis of polymer grid reinforced-soil retaining walls and its application to the design method

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ABSTRACT: Finite element analyses for the polymer grid reinforced-soil retaining walls are performed using the method which is capable of taking account of the displacement dependence property of the pull-out resistance of the polymer grid in soils. The reduction effect of the earth pressure acting on the wall and the wall deformation by the reinforcement is discussed. Furthermore, the application of the analytical results to the design method is proposed.

1 INTRODUCTION

In recent years, much interest has been taken in the method of soil reinforcement with the polymer grids. Most of the design methods for reinforced soil structures of this kind currently being employed are based on the theory of rigid-plasticity which takes no account of displacement and deformation of reinforcing material in soil (Netlon Ltd. 1984). However, for some types of earth reinforcements such as polymer grid reinforced soil structures where the soil on upper and lower sides of the polymer grid is partially continuous, a pull-out resistance of the polymer grid in soil depends on the displacement of the grid junction (Hayashi et al 1985).

In this paper, finite element analyses for the polymer grid reinforced-soil retaining walls are performed using the method which is capable of taking account of the mechanism of pull-out resistance of polymer grid in soil obtained from the pull-out tests on polymer grid (Ochiai & Sakai 1987). Analyses are performed for some various height of the wall, and spacing and length of the polymer grid. The relation between these parameters and the reduction effect of the earth pressure acting on the wall and the wall deformation is discussed. Finally, the application of the analytical results to the design method is proposed.

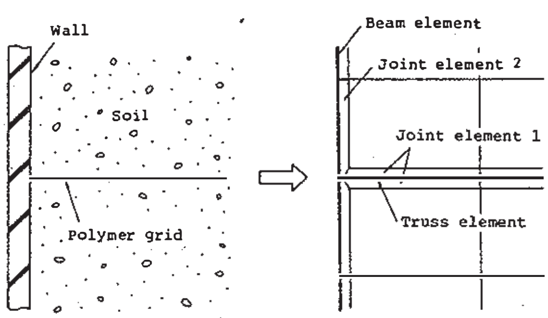
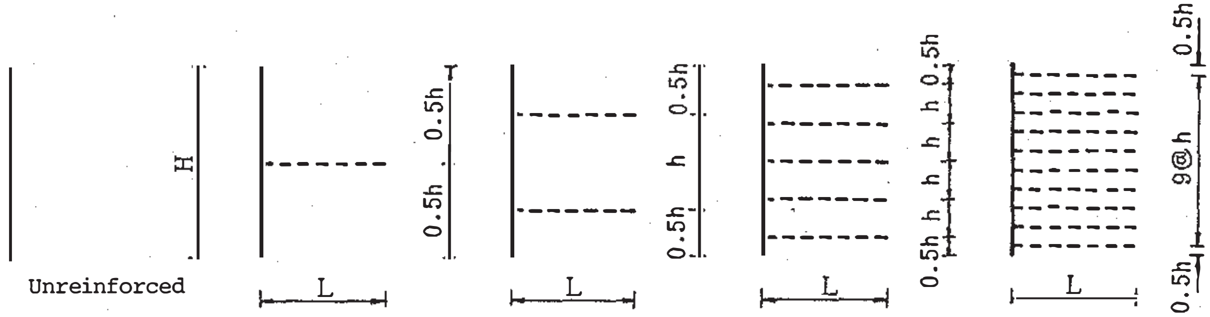


Fig.1 Modeling of polymer grid reinforced-soil retainig wall

2 ANALYSIS OF POLYMER GRID REINFORCED-SOIL RETAINING WALL

2.1 Modeling of polymer grid reinforced-soil retaining wall

For the case of deformation analysis of a reinforced soil structure with polymer grid, it is necessary to use an analytical method which is capable of expressing a behavior of discontinuous plane between polymer grid and soil with a peculiar friction. A modeling of the polymer grid reinforced-soil presented herein is a combination of the joint element expressing the property of discontinuous plane with the truss element transmitting the axial force only. This truss element whose ends are connected by the pin joint is used for modeling of polymer grid. The mechanism of pull-out resistance of the polymer grid in soil, especially the mobilizing process of the coefficents of pull-out resistance with shear displacement may be evaluated by introducing the dependence of shear



(a)Model-1 (b)Model-2 (c)Model-3 (d)Model-4 (e)Model-5

Fig.2 Analytical cases

displacement into a shear stiffness ks in the joint element.

The wall is modeled by the beam element which has a stiffness for bending moment and joint elements are also used on the boundary of soil-wall where the discontinuous plane may be caused. The finite element model for polymer grid reinforced-soil retaining wall is shown in Fig.1.

2.2 Analytical model and procedure

Fig.2 shows the cases to be studied, in which Model 1 is unreinforced one. The height of retaining wall, H, are 4.0 and 8.0m. The spacing, h, of the polymer grid laid in the backfill varies in h/H which are 1.0, 0.5, 0.2, and 0.1, and the length, L, of them varies in L/H which are 0.2, 0.4, 0.6 and 0.8. The end of the polymer grids are anchored to the wall.

The region of analyses is the foundation ground as well as the backfill because the retaining walls are not always built on the firm ground. Fig.3 shows an example of analytical models for the case of h/H=0.1 and L/H=0.8. As shown in Fig.3, the width of ground, B, equals to 4H, and the depth of it, D, equals to H, and the length of wall underneath the ground, Df, equals to 0.15H.

The soil backfill and the polymer grid used in analyses are a beach sand and an uniaxially orientated grid, SR-2, respectively. The relation between them resulted from the laboratory pull-out tests is used in the analyses in order to take account of the mechanism of pull-out resistance of the polymer grid in soil. In the analyses, Duncan-Chang model is used as a soil model. The parameters of soil backfill are determined by the results from laboratory tests and for those of foundation ground the past reference (Mitchell & Gardner 1971) are

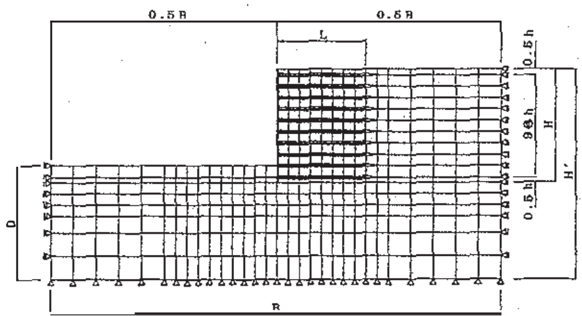


Fig.3 Finite element mesh

Table 1 Soil parameters

	γ' (kN/m³)	c (kN/m²)	ϕ (°)	K	n	R_f	ν
Backfill	17.7	0	38	1000	1.0	0.9	0.333
Foundation	7.8	0	35	300	0.5	0.7	0.333

Table 2 Material parameters

	E (kN/m²)	A (m²)	I (m⁴)
Polymer grid	1.62×10^{6} *	0.0012	—
Wall	2.45×10^{7}	0.18	4.86×10^{-4}

* Initial value

quoted. The material of the wall is a concrete of 18cm in thickness. Soil parameters of the backfill and the foundation ground are shown in Table 1 and material properties of the polymer grid and the wall in Table 2. Constant values of normal stiffness in the joint element are used in compression and tension sides, respectively. The values of compression side, kn1, and tension side, kn2, are 10^6kN/m^3 and 10^{-2}kN/m^3. The shear stiffness in the joint element used on the soil-wall boundary is constant value of 10^3kN/m^3. The deformation analyses by self weight of soil backfill are performed.

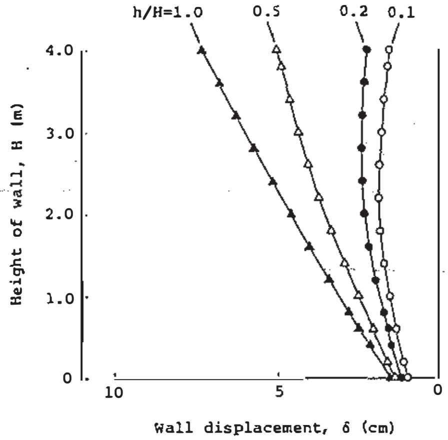


Fig.4 Distribution of wall displacement (H=4.0m, L/H=0.6)

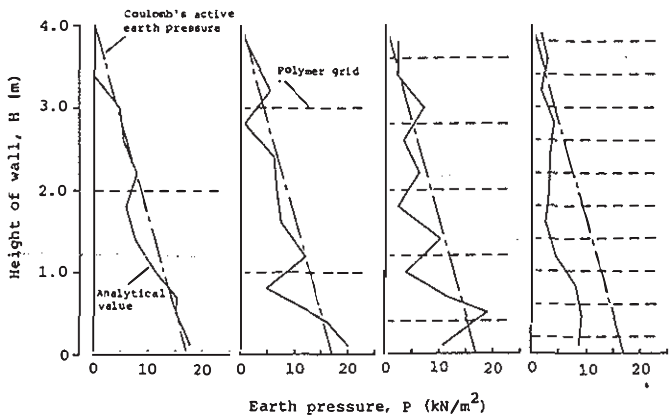


Fig.5 Distribution of earth pressure acting on the wall (H=4.0m, L/H=0.6)

2.3 Analytical results

(1) Property of the wall deformation and distribution of the earth pressure acting on the wall

Fig.4 shows the lateral displacement of the wall in the case of H=4.0m and L/H=0.6. The lateral displacement of the wall decreases as the spacing of the polymer grid becomes smaller. As for the distribution of the displacement, when the spacing is large of h/H=1.0, the displacement increases almost linearly from bottom toward top. On the other hand, in the case of h/H=0.5 the increment of the displacement in the upper part of the wall becomes smaller than the lower part and the shape of the deformation shows a lower bowed curve, the reason of which may be thought that the polymer grid laid in the upper part prevents the wall in the upper part from displacing. And moreover as the spacing becomes smaller of h/H=0.2 and 0.1, the inflection point of the displacement appears near the middle of the wall and the displacement has the maximum value at this point and decreases gradually at the upper part. In this manner, the shape of lateral displacement of the wall changes from a linear one to a bowed one, as the spacing of the polymer grid becomes smaller.

Fig.5 shows the distribution of the earth pressure acting on the wall in the case of H=4.0m and L/H=0.6. In this figure the solid lines and dot-solid lines indicate the analytical values and Coulomb's active earth pressure respectively, and the broken lines show the positions of the polymer grid laid in soil. The earth pressures of the part in which the polymer grids are laid are decreased by the reinforcement and the amount of earth pressures reduced becomes larger as the spacing of them becomes smaller. When the spacing is large, there is a difference of earth pressure between the parts in which the earth pressures are reduced and the parts not reduced, so that the distribution of the earth pressure is zigzag as a whole. On the other hand, in the case that the spacing is the smallest of h/H=0.1, there is less difference of earth pressure between the parts reduced and not reduced and the distribution of earth pressure becomes smooth. The distribution of earth pressure in this case is different from a triangular shape, and it is larger in the upper part of the wall and smaller in the lower part than Coulomb's active earth pressure. The distribution of earth pressure like this is associated with the condition of the wall deformation, of which shape is bowed, shown in Fig.4 and it may be thought that the soil in the upper part approaches the condition of the earth pressure at rest than the soil in the lower part.

(2) Relation between the spacing of the polymer grid and the reinforcing effects

Reductions of earth pressures resulted from the reinforcement in the case of L/H=0.6 are plotted against the spacing of the polymer grid in the backfill in Fig.6. Here, the reduction ratio of the earth pressures, Rp, is expressed by the following equation;

$$Rp = 1 - (Pg / Po) \quad (1)$$

in which Po is total force of Coulomb's active earth pressure acting on the wall in the unreinforced case and Pg is that of earth pressure resulted from the analysis with reinforced soil backfill. And the spacing, h, is normalized by the wall height, H, and the ratio, h/H, is used as an abscissa in Fig.6. The relation between

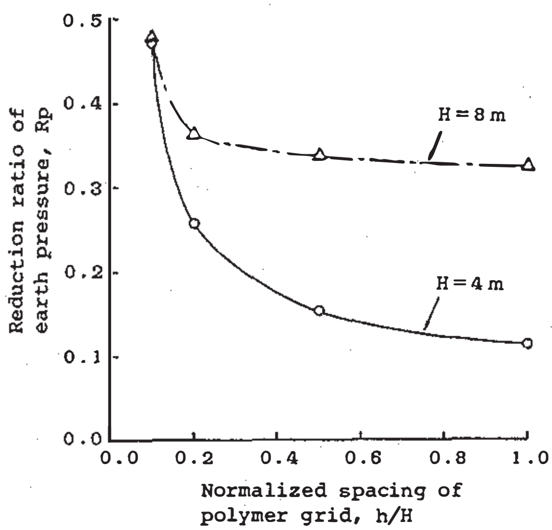


Fig.6 Relation between reduction ratio of earth pressure and spacing of polymer grid (L/H=0.6)

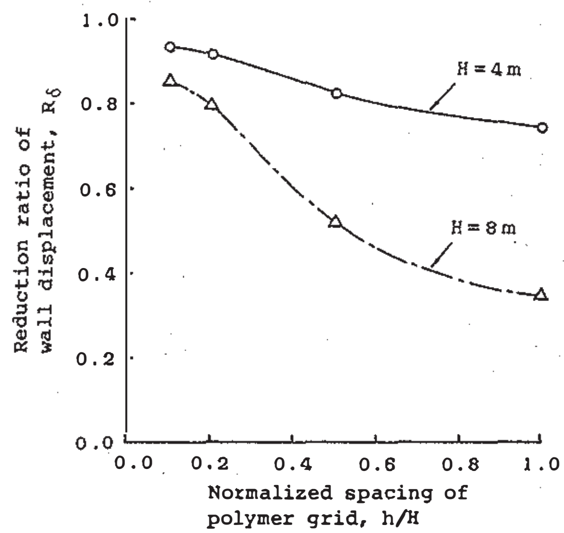


Fig.7 Relation between reduction ratio of wall displacement and spacing of polymer grid (L/H=0.6)

the reduction ratio of earth pressure and the normalized spacing of the polymer grid is like a hyperbola and the reduction ratio of earth pressure decreases rapidly as the spacing becomes smaller. And although the values of reduction ratio are different due to the difference of the wall height, these differences become smaller as the spacings become smaller and reduction ratios in both height become almost equal in the case of h/H=0.1.

Fig.7 shows the relation between the reduction ratio of lateral displacement of the wall, R_δ, and the normalized spacing of the polymer grid, h/H, in the case of L/H=0.6. Here, the reduction ratio, R_δ, is expressed by the following equation;

$$R_\delta = 1 - (\delta g / \delta o) \qquad (2)$$

where δg and δo are maximum values of the lateral displacements of the walls with and without reinforced soil backfill, respectively. The reduction of the wall displacement by the reinforcement of backfill becomes larger as the spacing becomes smaller. And although the values of reduction ratio are different due to the difference of the wall height, these differences become smaller as the spacings become smaller as well as the case of the earth pressure.

(3) Relation between the length of the polymer grid and the reinforcing effects

Reductions of earth pressures resulted from the reinforcement in the case of h/H=0.1 are plotted against the normalized length of the polymer grid in the backfill in Fig.8. The reduction ratios of the earth pressures have the almost same values independently of the wall height, and they show the salient distributions, which have a peak at L/H=0.6, against the normalized length of the polymer grid. Accordingly, from the results of Figs.6 and 8, it may be said that the earth pressure acting on the wall can be reduced about 50 percent at a maximum against Coulomb's active earth pressure.

Fig.9 shows the relation between the reduction ratio of the wall displacement and the normalized length of the polymer grid in the case of h/H=0.1. Although the values of reduction ratio are different due to the difference of the wall height, both of them increase as the length of the polymer grid becomes longer.

By the way, as shown in Fig.10, the earth pressure acting on the wall is changed according to the condition of the wall deformation and it shifts from the condition of the active earth pressure to the condition of the earth pressure at rest as the wall displacement becomes smaller. On the other hand, the earth pressure is reduced by the tensile force acting on the polymer grid. And so it may be supposed that finally the earth pressure acting on the wall becomes such a distribution as shown by the solid line in Fig.10. Whereas it seems that the amount of the earth pressure reduced, which is shown by the shade in Fig.10, becomes larger as the length of polymer grid becomes longer, at the same time the distribution of the earth pressure shown by the broken line in Fig.10 approaches rapidly to the distribution of the earth pressure at rest according to the reduction of the wall displacement. And

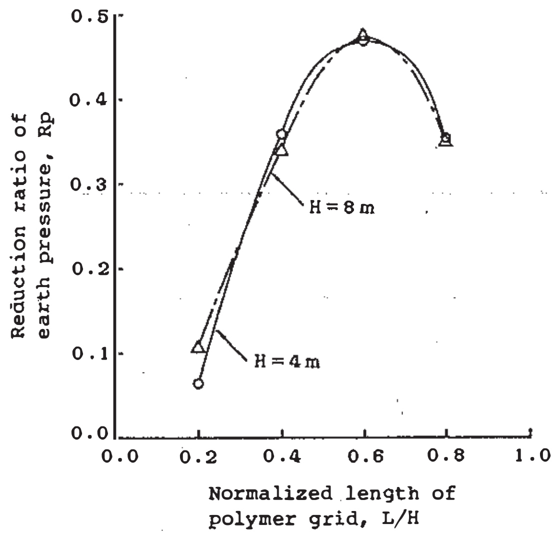


Fig.8 Relation between reduction ratio of earth pressure and length of polymer grid (h/H=0.1)

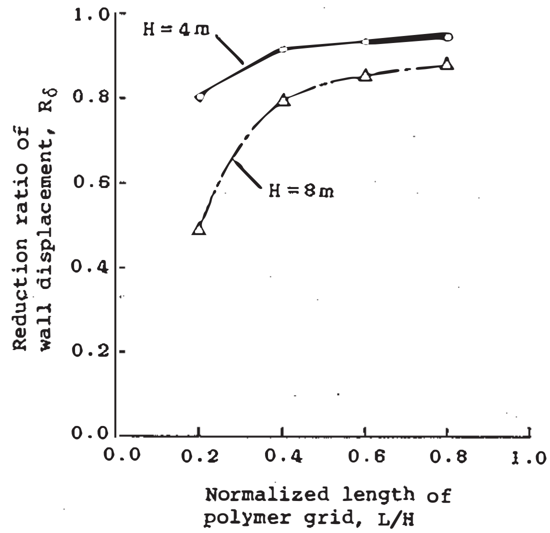


Fig.9 Relation between reduction ratio of wall displacement and length of polymer grid (h/H=0.1)

then the final earth pressure acting on the wall seems to be determined by the quantitative relation between them. It can be supposed that the reason why the reduction ratio of the earth pressure based on Coulomb's active earth pressure without reinforced soil backfill decreases between L/H=0.6 and L/H=0.8 is that the increment of the earth pressure due to the reduction of the wall displacement is larger than that of the earth pressure reduced by the reinforcement. Accordingly when the length of the polymer grid becomes longer than some value, the rear part of the polymer grid plays the part of the anchor and reduces the wall displacement, and at the same time the distribution of the earth pressure approaches the condition of the earth pressure at rest. And so it can be said that there exists the length of the polymer grid which minimizes the amount of the earth pressure acting on the wall.

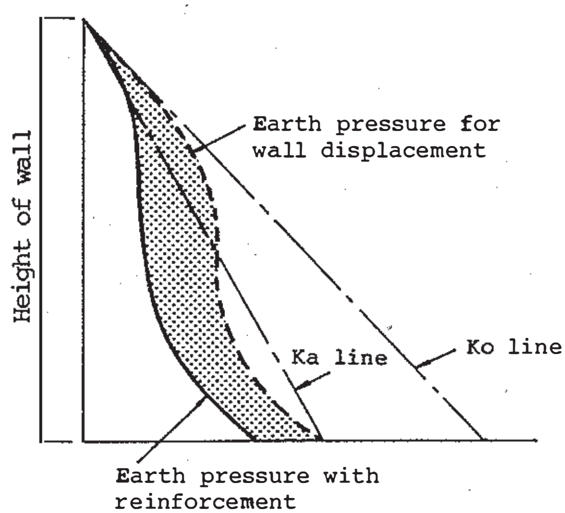


Fig.10 Distribution of earth pressure for wall deformation and reinforcement

3 APPLICATION OF THE ANALYTICAL RESULTS TO THE DESIGN METHOD

Up to this time, in the design of the retaining wall with polymer grid reinforced soil backfill, the stability for sliding, overturning and bearing failure etc. has been investigated by assuming that a reinforced soil wall behaves as a rigid gravity structure. It is the investigation of stability based on what is called the rigid-plasticity theory and does not mention anything about the displacement and deformation of the wall and reinforcing material caused by the self weight of soil backfill and surcharge. However, in the practical constructions the deformation of the structure is not seldom an important design factor because of the recent works with adjacencies in the city and importance of a fine view based on the environmental assessment. And then from now on, it will become a problem in the design how large the wall deformation is. In other words, the check of allowable displacement of the wall will be required.

The numerical methods for which the finite element method stands are one of the powerful methods to grasp the deformation of the structure. However, there is a limitation of time and cost to

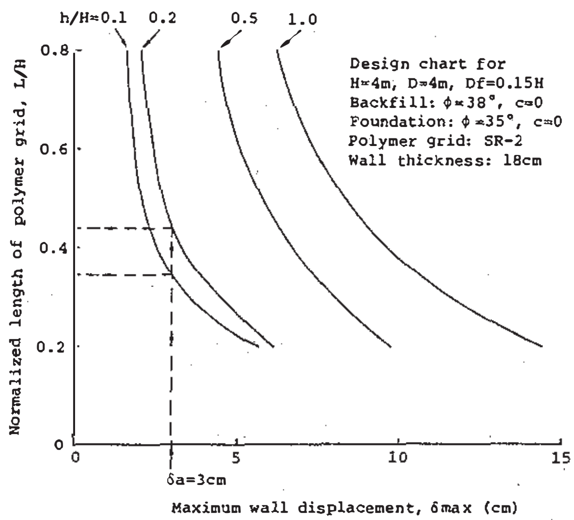


Fig.11 Design chart for checking wall displacement

analyse by such numerical methods on the design condition in each case, so that it seems to be very significant that the procedure to investigate the amount of deformation easily and quickly for the comparatively simple design condition is proposed. The procedure to check the amount of deformation of the reinforced soil wall using the design chart obtained from the analytical results is presented as the following. This is useful to investigate the wall deformation in the stage of the preliminary design.

At first define the design condition of the problem. That is, define geometry such as the height of wall, H, the length of wall underneath the ground, Df, and the depth of ground, D, and the material properties such as parameters of soil backfill and foundation ground and those of polymer grid and wall. To illustrate the design procedure, consideration will be given to the condition in the analyses mentioned above, as shown in Fig.11.

Next, determine the spacing and the length of the polymer grid for allowable displacement of the wall. The relations between the maximum lateral displacement of the wall and the length and spacing of the polymer grid obtained from the analytical results for given design conditions are shown in Fig.11. The design chart is entered for a known value of allowable displacement, moving vertically until the normalized spacing, h/H, is reached, and then sidewards; the required normalized length of the polymer grid, L/H, may then be read off. When there are more than one value of L/H for a given allowable displacement, the case in which the total length of the polymer grid per unit height, 1m, of the wall, Lt/H, is the smallest should be selected. In the case of an example shown in Fig.11, the required values of (L/H,h/H) for a given allowable displacement, δa=3cm, are (0.44,0.2) and (0.33,0.1). Therefore the value of Lt/H are 2.2 and 3.3 m/m, respectively, and then L/H=0.44 and h/H=0.2 are adopted finally.

4 CONCLUSIONS

The leading conclusions are summarized as the following.

(1) The earth pressure acting on the wall decreases and the distribution of it becomes smooth, as the spacing of the polymer grid becomes smaller.

(2) When the spacing of the polymer grid is small of h/H=0.1, the earth pressure acting on the wall is controlled by the length of the polymer grid independently of its spacing and is minimized in the case of L/H=0.6 and its value is about 50 percent of Coulomb's active earth pressure.

(3) The wall displacement decreases, as the spacing of the polymer grid becomes smaller and the length of it becomes longer. And the shape of the wall deformation changes from a linear one to a bowed one, as the spacing of the polymer grid becomes smaller.

(4) The procedure to investigate approximately the amount of wall deformation in the stage of preliminary design is presented using the design chart in which the relation resulted from analyses between the maximum displacement of the wall and the length and spacing of the polymer grid is shown.

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