PARAMETRIC SEISMIC ANALYSIS OF TIERED GEOSYNTHETIC-REINFORCED SEGMENTAL RETAINING WALLS

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ABSTRACT: This study presents Finite Element Analysis of seismic behaviour of tiered geosynthetic reinforced soil retaining walls. A finite element computer program, Plaxis, is used to investigate the effects of a number of factors. These factors are; wall height (H), ratios of geosynthetic reinforcement (GR) length to wall height for the upper and the lower wall (L_1/H and L_2/H), ratio of distance between two walls to wall height (D/H), vertical spacing of geosynthetics (S_v), stiffness of geosynthetics (EA_{GR}), Elasticity Modulus of reinforced and retained soil (E_r), and coefficient of damping (α and β). A factorial design analysis is set up to discuss the results. The most important parameter after the height of the wall that controls the amount of deformation is the D/H ratio, which indicates that a bigger berm is very useful in reducing the amount of deformation. Another major conclusion is that the length of the reinforcement in the lower wall is slightly more effective in reducing the deformation at the top than the length of the geosynthetic reinforcement in the upper wall, for granular soils.

1 INTRODUCTION

Reinforced soil is the technique where tensile elements are placed in the soil to improve stability and control deformation. In this technique, the reinforcements must intersect potential failure surfaces in the soil mass. Strains in the soil mass generate strains in the reinforcements, which in turn, generate tensile forces in the reinforcements. These tensile forces act to restrict soil movements and thus impart additional shear strength.

The technique of reinforced soil is not a new concept. For many centuries, civilizations have sought effective methods to construct stable soil retaining structures. Ancient civilizations incorporated layers of natural tensile elements to reinforce the soil to construct a stable structure.

In a modern context, reinforced soil has become a viable and cost-effective technique only over the last thirty years. This was brought about by the development of geosynthetic reinforcements engineered from strong and durable polymers. Geosynthetic reinforcements enable substantial tensile loads to be supported at defined deformations over extended design lives. The inclusion of geosynthetic enables the use of poorer quality soils to be used as structural components. The construction gains extra flexibility with the use of geosynthetics in design. Geosynthetics can be made strong under tension, typically ductile, easy to handle and to construct with. Also, depending on the type of the polymer, they can be inert and durable in many applications. Consequently, the use of geosynthetics as soil reinforcement is attractive, allowing flexibility in design (Anon. 1990).

Geosynthetic-reinforced retaining walls performed well during recent strong earthquakes and only a few catastrophic failures have been reported. This is not because of an appropriate seismic design but mostly because of the conservatism of static design procedures. So many researches are trying to determine a more proper seismic design with decreasing conservatism and taking economy into account.

The researches carried out using geosynthetics were mostly for determining the stress/strain distribution and the failure mechanisms of the wall. The aim of this study is to investigate and determine the required dimensions and material types for tiered geosynthetic-reinforced walls under earthquake loading conditions. The analysis will be carried out using a finite element program Plaxis, and the results will be evaluated using a statistical program SPSS.

2 METHODOLOGY

2.1 *Modelling with Plaxis*

Our discussion will focus on tiered segmental retaining walls with geosynthetics as reinforcement and concrete blocks as facing.

2.1.1 *Model geometry*

Design geometry is constructed with a plane strain model of which the typical cross-section is seen in Figure 1. In longitudinal direction the wall is assumed to continue infinitely.

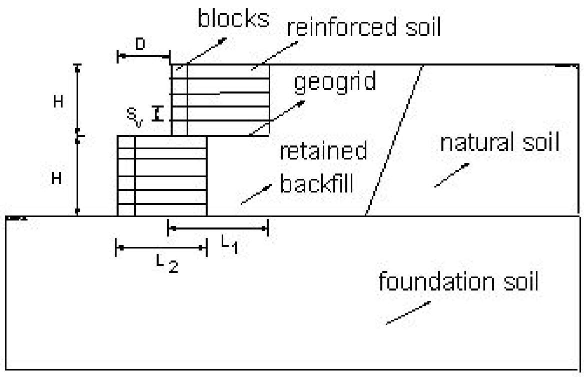

Figure 1 Plane strain geometry model of design

Dimensions of design, wall heights, reinforcement length to wall height ratio, vertical spacing of the reinforcing elements and ratio of the distance between two walls to wall height are changed according to the limit conditions specified in standards. These values of the corresponding parameters are given in Table 1.

Table 1 Measure of design parameters

Parameters	low level	high level
Wall height (H)	4 m	6 m
ratio of GR length of the first (upper) wall to wall height, L_1/H	0.8	1.4
ratio of GR length of the second (lower) wall to wall height, L_2/H	0.6	1.5
ratio of the distance between two walls to wall height, D/H	0.1	0.5
vertical spacing of GR, S_v	0.25 m	0.50 m

Backfill width is extended to 25m (average value over the depth) behind the facing giving a width to height ratio B/H = 2 for the backfill model to capture the yielded zone in the retained zone during seismic loading.

2.1.2 *Material properties*

Behavior of granular soil used as reinforced and retained soil in the design is modeled by means of elasto-plastic constitutive law. More particularly, the soil material is assumed linear elastic for stress states within the yield surface and perfectly plastic at failure, governed by the Mohr-Coulomb criterion. Possible softening of the soil due to large strains associated with the extensible reinforcement is ignored at that stage. A non-associated flow is considered with a dilatancy angle, φ, equal to half of friction angle ϕ. It is likely to assume from the beginning that under dynamic loads soils and soil-structure interactions show very small displacements. This assumption may lead us to be content with elastic models with a shear modulus G, a bulk modulus K and a Poisson's ratio, ν. The consisting material behavior is assumed to be linearly elastic under dynamic excitation with very small displacements.

Since only long term effects are considered and ground water table is assumed well below design, undrained behavior of the soil is not taken into account. Hence material type is set to drained.

Design is assumed to be built on a competent foundation for which foundation collapse or excessive settlement is not a potential source of instability. The foundation soil is assumed as a firm layer that extends to great depths.

Elasticity modulus is known to be changing with confining pressure, however, for simplicity in the current study elasticity modulus is held constant for the duration of the numerical experiment including construction. Use of a constant elasticity modulus for the soil reduces computation time for both static and dynamic loading simulations.

Soil material properties used in analysis are given in Table 2. Since our aim is to determine the effects of different parameters, some parameters in this table have more than one value that will be used in factorial design.

Stress-strain behavior of geosynthetic reinforcing elements is simulated as linear elastic. This is considered sufficient as the stress level in the service condition is rather low. Long-term deformations of the model wall are deemed negligible. Therefore creep is not considered. In our design, geosynthetics are simulated as slender objects with a normal stiffness but with no bending stiffness or compressive strength. The cross-sectional area is equivalent to geosynthetic area.

Table 2 Soil material properties

Parameters	Name	reinforced / retained soil	foundation soil
material model	Model	MC	MC
Type of behaviour	Type	drained	drained
dry soil weight (kN/m^3)	γ_{dry}	17	20
elasticity modulus (kN/m^2)	Low level	75	150
	High level	125	
poisson's ratio	ν	0.35	0.4
cohesion (kn/m^2)	c.	2	2
friction angle (°)	ϕ	35	45
dilatancy angle (°)	$\psi = 0.5\ \phi$	18	23

Mechanical properties of the reinforcing elements are ultimate strength, T_{ult}, and axial stiffness, EA, which are given in Table 3. Strength parameters describing geosynthetics are taken directly from actual product specifications. Self weight of the reinforcement is assumed to be negligible.

Table 3 Geosynthetics properties

Parameters	Name	PP-GR
Rib size (Mm)	a*b	28*40
Mass per unit area (g/m^2)	μ	400
Axial stiffness (kN/m)	low level EA_{GR}	5,000
	high level EA_{GR}	10,000
Ultimate tensile strength (kN/m^2)	T_{ult}	45

In our parametric analysis, it is found adequate to model the facing by modular blocks which are especially constructed with geosynthetic reinforcing materials. Modular block facing elements are modeled as soil elements having dimensions 0,5m and 0,25m as width and height, respectively. Material properties of modular blocks are given in Table 4.

Table 4 Material properties of modular block facing

parameters	Name	Modular block facing
material model	model	MC
Unit weight (kN/m^3)	γ_{dry}	20
elasticity modulus (kN/m^2)	E	30,000
poisson's ratio	ν	0.1
cohesion (kn/m^2)	c.	200
friction angle (°)	ϕ	35

2.1.3 *Interaction*

Interaction between soil and reinforcing geosynthetics is modelled at both sides by means of interfaces. These interfaces with a virtual thickness will allow us to specify a reduced friction related with the friction of soil. An elasto-plastic model is used to describe the behavior of these interfaces. In our design, there are interfaces between foundation and retained and reinforced soil, between geosynthetics and surrounding reinforced soil and also there are interfaces between all block elements of the wall. $R_{interface}$, strength reduction factor, is chosen as 0.7 for all these interfaces.

2.1.4 *Boundary conditions*

Boundaries are placed far enough not to interact with stress and strain distribution inside the structure. As boundary conditions, absorbent boundaries are applied where increments of stresses on boundaries are assumed to be absorbed by viscous dampers. This is done to model an infinite domain and to prevent artificial stress wave reflections generated at the finite element model boundaries from entering the model and influencing the results.

In dynamic analysis, it is assumed that dampers are placed all along the boundaries. Vertical and shear stresses absorbed by dampers are proportional to the wave velocity and they can be defined as

$$\sigma_n = -C_1 * V_p * \rho * \ddot{u}_x \quad \text{and} \quad \tau = -C_2 * V_s * \rho * \ddot{u}_y \qquad (1)$$

where V_p ,is compression wave velocity, V_s is shear wave velocity, ρ is material density, $\ddot{u}x$ and $\ddot{u}y$ are accelerations in x and y directions. C_1 and C_2 are Newmark coefficients defining the effect of absorption. C_1 corrects the dissipation in the direction normal to boundary and C_2 in tangential direction.

In our analysis, in order to have a reasonable absorption of compression and shear waves, Newmark coefficients C_1 and C_2 are taken as 1 and 0.25, respectively.

2.1.5 *K_o procedure and staged construction*

Before applying dynamic loading, objects that are not active are deselected in the initial geometry configuration geometry. Initial effective stresses using K_o procedure are then generated. Aim of this procedure is to find out the initial vertical and horizontal stresses on the soil due to its own weight. In this method, K_o is calculated by Jaky's formula (1-sinϕ).

Wall is constructed in lifts of 50cm high. Gravitational force of each lift is applied in increments. Displacements, stresses and strains are calculated and monitored in reinforcement and soil throughout the construction process, in other words, numerical model at each stage is solved to equilibrium with a prescribed tolerance before placing the next facing block, soil lift and reinforcement layer.

2.1.6 *Dynamic loading*

Wu (1994) proposed an equation for the fundamental frequency of vibration for a two-dimensional, linear elastic medium of width B and height H contained by two rigid vertical boundaries and a rigid base and subject to horizontal base excitation as

$$f = \frac{1}{4H}\sqrt{\frac{G}{\rho}}\sqrt{1+\left(\frac{2}{1-\nu}\right)\left(\frac{H}{B}\right)^2} \qquad (2)$$

where f is the frequency in Hz, G, ν and ρ are shear modulus, density, and Poisson's ratio of the elastic medium, respectively.

In case of an infinitely wide medium ($B\rightarrow\infty$) above equation becomes the fundamental frequency of a one-dimensional elastic medium with height H. Inserting the values of our parameters used in the design, above equation gives us the natural frequency of our model as 4.

Rayleigh, and after him most of the researchers, found it adequate to write damping as a linear combination of the mass and stiffness matrix as $C = \alpha_R M + \beta_R K$ where α_R (alpha) and β_R (beta) are scalars and called Rayleigh coefficients (Ergun 2002).

α_R and β_R coefficients are calculated for a given damping ratio with the following equation

$$\begin{Bmatrix}\alpha\\ \beta\end{Bmatrix} = \frac{2*C}{\varpi_m + \varpi_n}\begin{Bmatrix}\varpi_m\varpi_n\\ 1\end{Bmatrix} \qquad (3)$$

where C is the damping ratio, taken as five and 10 per cent in our analysis, and ϖ_m and ϖ_n are the highest frequency contributing significantly to the dynamic response and fundamental frequency of the system, respectively. Fundamental frequency of our system has been calculated as four Hz and the highest frequency contributing to the system has also been taken as four Hz as a predominant frequency closer to the fundamental frequency of the wall induces a significantly larger lateral displacement in the wall.

Values for α_R and β_R are given in Table 5 for damping ratios five and 10 per cent.

Table 5 Rayleigh coefficients for different damping ratios used in the design

Damping ratio	α_R	β_R
5 per cent	0.2	0.0125
10 per cent	0.4	0.025

After static equilibrium is achieved (end of construction stage), full width of the foundation is subjected to variable-amplitude harmonic ground motion, as shown in Figure 3.

Excitation input is applied in terms of prescribed displacement. This acceleration record is applied horizontally to all nodes at the bottom at equal time intervals (time interval between recorded data points) of Δt = 0.05 s. The mathematical expression for input acceleration is given by Hatami and Bathurst (2000) as

$$\ddot{u}(t) = \sqrt{\beta e^{-\alpha t} t^{\xi}}\ \sin(2\pi f t) \qquad (4)$$

where α= 5.5, β = 55, and ξ = 12 are constant coefficients, f is the base acceleration frequency chosen as four Hz to represent a typical predominant frequency of medium- to high-frequency content earthquakes, and, t is the time. Frequency is chosen close to the fundamental frequency of the wall system as record with a predominant frequency closer to the fundamental frequency of the wall induces a significantly larger lateral displacement in the wall. Resulting horizontal peak amplitude, k_h, using these parameters is 0.24 g, where g is the acceleration of gravity. Constant coefficients in the equation are chosen so that the horizontal peak acceleration will be 0.24 g because Turkish Earthquake Regulation 1998 requires maximum horizontal acceleration amplitude to be 0.24 g in earthquake region 1 (like İstanbul - Turkey) and for structures like retaining walls.

2.2 *Factorial design analysis by SPSS*

Effects of eight variables namely; wall height (H), ratios of GR length to wall height (L_1/H and L_2/H) for the lower and upper wall, ratio of distance between two walls to wall height (D/H), vertical spacing of GR's (S_v), Elasticity Modulus of reinforced and retained soil (E_r), axial stiffness of geosynthetics (EA_{GR}), and coefficients of damping (α and β) are investigated in this study. It is found adequate to use a special statistical method, factorial design analysis using a statistical computer program named SPSS, to examine these parameters (Box et. Al. ,1978). We are interested in characterizing tiered retaining walls reinforced with geosynthetics under earthquake; that is we want to determine which factors affect the stability of these walls under dynamic loading. By a factorial design, it is possible to investigate all combinations of the levels of these eight factors in each complete trial. Response of the model wall is represented in terms of facing displacement. Due to its significance in design and performance of retaining wall structures under both static and seismic loading conditions, this parameter is selected as the representative one in our design.

In this design of 256 experiments only eight of the 255 degrees of freedom correspond to main effects, and only 28 degrees of freedom correspond to two-factor interactions. Remaining 219 degrees of freedom are associated with three-factor and higher interactions. So it can reasonably be assumed that certain higher-order interactions are negligible, then information on the main effects and low-order interactions may be obtained by running only a fraction of the complete factorial experiment. We chose our basic design of 2^{8-3}_{IV} fractional factorial by confounding factors F, G and H by interactions ABC, ABD and BCDE, respectively.

This is a resolution of IV where IV resolution designs are designs in which no main effect is aliased with another main effect or with two-factor interaction but two-factor interactions are aliased with each other, consequently it is convenient to assume that three-factor and higher interactions are negligible. We choose resolution IV that has the highest possible resolution consistent with the degree of fractionation required. The higher the resolution, the less restrictive the assumptions that are required regarding which interactions are negligible in order to obtain a unique interpretation of the data.

3 RESULTS

32 runs using 8 factors with two levels are carried out on granular soil. The factorial design configuration and corresponding wall response is given in Table 6.

3.1 *Effects of factors*

These outcome data in Table 6 are used for regression evaluation in SPSS. In analysis, a confidence level of 95% is assumed. Corresponding ANOVA (analysis of variance) table and coefficient effects of the factors are given in Table 7.

In regression statistics part, our R-squared value is 0.91 which is close enough to one for a screening experiment. In other words, 91% of the variability in wall deformation is explained by the factors given in effect coefficients table.

In ANOVA part, df is degree of freedom of regression and residual part. Regression is the line formed by the effect of estimated main factors. Residual is the sum of the ineffective factors and error term and SS is the sum of squares.

Dividing SS by df mean square (MS) values both for regression and residuals are obtained. Ratio of MS values between regression and residual is then calculated and called F. F implies an upper one-tail critical region. This F value is compared with a significance value that is tabulated for given confidence levels. Our calculated F value in Table 7 is 27.79 and greater than significance F value 4.69E-10. This states that analyzed factors do have effects on the output.

In the effect coefficients part, coefficients of the factors and interactions are given. Comparing these coefficients important factors are determined. The highest coefficients belong to the most important factors. Analyzing these coefficient values it is seen that main factors A (H), D (D/H), F (EA_{GR}) and C (L_2/H), affect the maximum wall displacement most.

We define the P-value as the smallest level of significance, α, at which the data are significant. Analyzing Table 7 all factors determined as important ones have P values higher than 95% P value, so all these factors do have effect on the output. The higher the P value, the more important the effects of factors are.

To assist in interpreting the results of this experiment, it is helpful to construct a graph showing average responses at each treatment combination. Figure 2 shows the average response at different levels of factors.

3.1.1 *Main factort A (H)*

Effect coefficient of main factor A is 14.52 and highest among the others in other words, most effective on the output. This value is positive that means output increases with increasing wall height. That is why wall height (H) should be decreased in order to minimize the wall displacement.

3.1.2 *Main factor D (D/H)*

This variable has a negative main effect -3.77; that is increasing the variable moves the amount of displacement from the target downward. Results show us that wall displaces more when the two walls, upper and lower one, are close to eachother. Since less displacement is required, high levels of D/H ratio can be recommended.

3.1.3 *Main factor F (EA_{GR})*

Effect of factor F (EA_{GR}) is -2.93 and this suggests that increasing B from low level to high level will decrease the deformation. So high levels of geosynthetics stiffness are recommended to decrease wall displacement.

3.1.4 *Main factor C (L_2/H)*

Effect coefficient of factor C has a negative value -2.68 which is inversely proportional with the output. In other words, increasing L_2/H will decrease the displacement which is required so high levels of this factor should be used for a safe design.

3.1.5 *Other factors*

As can be seen from Figure 2, other factors do not have much effect on the output as their lines of effects are nearly horizontal. In general minimum displacement is attained at high levels of the factors B (L_1/H), G (E_r) and H (damping). Same result can also be obtained from the ANOVA table as all these factors have smaller effect coefficients comparing to the important ones.

Table 6 Factorial design configurations and wall response as max. wall displacement of wall face

run	A (H) (m)	B (L_1/H)	C (L_2/H)	D (D/H)	E (S_v) (m)	F = ABC (EA_{GR}) (kN/m)	G = ABD ($E_{reinforced}$ = $E_{retained}$) (kN/m)	H = BCDE (damping) %	max. horizontal displacement of wall (mm)
1	4	0.8	0.6	0.1	0.25	5.000	75.000	5	20.78
2	6	0.8	0.6	0.1	0.25	10.000	125.000	5	53.51
3	4	1.4	0.6	0.1	0.25	10.000	125.000	10	11.39
4	6	1.4	0.6	0.1	0.25	5.000	75.000	10	47.26
5	4	0.8	1.5	0.1	0.25	10.000	75.000	10	16.1
6	6	0.8	1.5	0.1	0.25	5.000	125.000	10	56.01
7	4	1.4	1.5	0.1	0.25	5.000	125.000	5	13.83
8	6	1.4	1.5	0.1	0.25	10.000	75.000	5	37.77
9	4	0.8	0.6	0.5	0.25	5.000	125.000	10	16.34
10	6	0.8	0.6	0.5	0.25	10.000	75.000	10	37.63
11	4	1.4	0.6	0.5	0.25	10.000	75.000	5	14.24
12	6	1.4	0.6	0.5	0.25	5.000	125.000	5	39.91
13	4	0.8	1.5	0.5	0.25	10.000	125.000	5	13.43
14	6	0.8	1.5	0.5	0.25	5.000	75.000	5	42.42
15	4	1.4	1.5	0.5	0.25	5.000	75.000	10	13.65
16	6	1.4	1.5	0.5	0.25	10.000	125.000	10	31.59
17	4	0.8	0.6	0.1	0.50	5.000	75.000	10	31.87
18	6	0.8	0.6	0.1	0.50	10.000	125.000	10	48.85
19	4	1.4	0.6	0.1	0.50	10.000	125.000	5	14.74
20	6	1.4	0.6	0.1	0.50	5.000	75.000	5	74.51
21	4	0.8	1.5	0.1	0.50	10.000	75.000	5	19.59
22	6	0.8	1.5	0.1	0.50	5.000	125.000	5	57.56
23	4	1.4	1.5	0.1	0.50	5.000	125.000	10	18.96
24	6	1.4	1.5	0.1	0.50	10.000	75.000	10	40.6
25	4	0.8	0.6	0.5	0.50	5.000	125.000	5	21.65
26	6	0.8	0.6	0.5	0.50	10.000	75.000	5	57.47
27	4	1.4	0.6	0.5	0.50	10.000	75.000	10	16.36
28	6	1.4	0.6	0.5	0.50	5.000	125.000	10	39.37
29	4	0.8	1.5	0.5	0.50	10.000	125.000	10	11.25
30	6	0.8	1.5	0.5	0.50	5.000	75.000	10	39.33
31	4	1.4	1.5	0.5	0.50	5.000	75.000	5	16.48
32	6	1.4	1.5	0.5	0.50	10.000	125.000	5	31.52

Table 7 ANOVA (analysis of variance) table and coefficient effects of the factors

Regression Statistics	
Multiple R	0.95
R Square	0.91
Adjusted R Square	0.87
Standard Error	6.09
Observations	32

ANOVA					
	df	SS	MS	F	Significance F
Regression	8	8241.79	1030.22	27.79	4.69E-10
Residual	23	852.66	37.07		
Total	31	9094.44			

Coefficient Effects				
	Coefficients	Standard Error	t Stat	P-value
Intercept	31.44	1.08	29.21	1.10E-19
A (H)	14.52	1.08	13.49	2.06E-12
B (L_1/H)	-2.55	1.08	-2.37	2.66E-02
C (L_2/H)	-2.68	1.08	-2.49	2.04E-02
D (D/H)	-3.77	1.08	-3.50	1.91E-03
E (S_v)	2.32	1.08	2.16	4.18E-02
F = ABC (EA_{gt})	-2.93	1.08	-2.73	1.20E-02
G=ABD E_r	-1.44	1.08	-1.34	1.93E-01
H=BCDE(damping)	1.65	1.08	1.53	1.39E-01

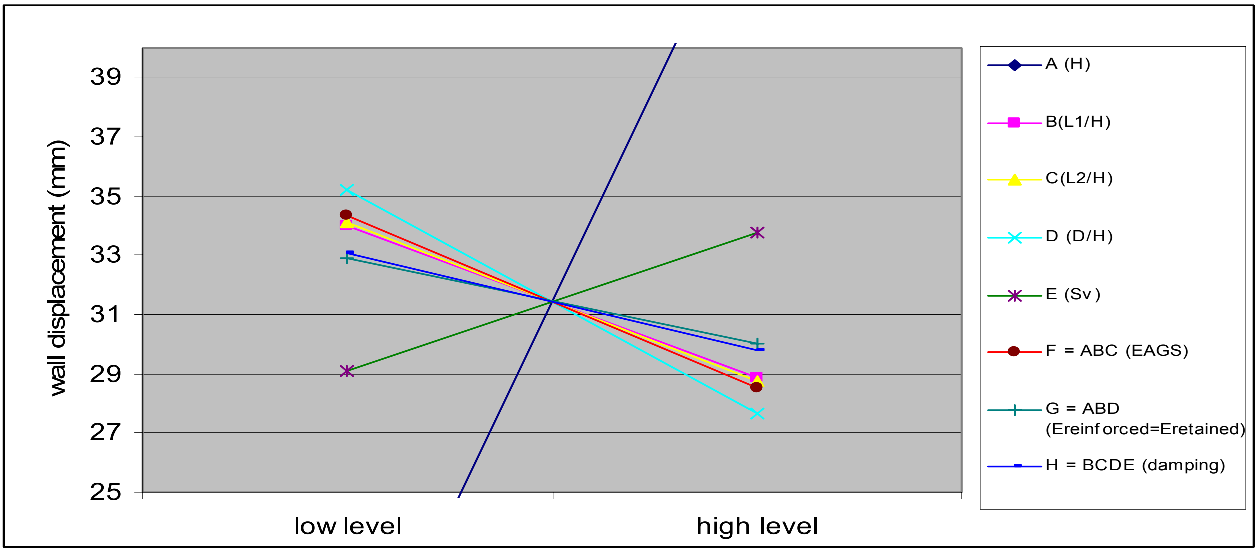

Figure 2 Average wall displacement vs. levels of main factors

4 CONCLUSION

There are several conclusions that can be derived based on the findings of the performed analysis. Here only the major conclusions will be mentioned.

The numerical analysis indicates as expected, that the height of the wall is the most important parameter effecting the horizontal deformation on the top of the wall.

The most important parameter after the height of the wall that controls the amount of deformation is the D/H ratio, which indicates that a bigger berm is very useful in reducing the amount of deformation. Considering that the deformation increases with increasing height, this is especially important with rather high walls.

The numerical analysis further indicates that the stiffness of the reinforcement (EA_{GR}) contributes to the deformation slightly less than the berm width (D/H).

Another major conclusion is that the length of the reinforcement in the lower wall is slightly more effective in reducing the deformation at the top than the length of the geosynthetic reinforcement in the upper wall, for granular soils.

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