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Effects of Wall-Soil-Structure Interaction on Seismic Response of Retaining Wall

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EFFECTS OF WALL-SOIL-STRUCTURE INTERACTION ON SEISMIC RESPONSE OF RETAINING WALL

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ABSTRACT

Retaining walls have suffered damages under past earthquakes. Usually the analyses do not consider the retained soil's interaction with the wall, which takes place during dynamic conditions. The consideration makes the wall-soil system more flexible than the wall alone. The conditions of separation of wall (during interactions) again change the dynamic characteristics of the assumed wall-soil system that needs to be addressed.

The paper presents a study on the behavior of the retaining wall under static as well as seismic conditions considering above aspects. The wall-soil interaction model incorporates the modeling of interface between them. The system is idealized as a plane strain two-dimensional model and base acceleration in the form of typical earthquake motion (Uttarkashi, October 20, 1991, India) is represented as external loading. The study concludes with important results, which are useful for researchers, scientists and those involved in analyses and design of retaining walls.

INTRODUCTION

In study of retaining wall, it is very important to model the phenomenon through which earth pressure is transferred to wall and hence, the modeling of soil-wall interface becomes important.

The study presents the seismic response of retaining wall when soil-wall system is modeled as continuum as well as when modeled with interface. In this work emphasis has been made on the modeling of interface between structure and soil and the difference in displacement and stress response presented with their variation. Stress and displacement values for both cases, with and without interface, are evaluated using finite element analysis and presented for static and seismic conditions. The problem has been analyzed using ANSYS.

MODEL PARAMETERS

Dimensions for the cantilever retaining wall under study are mentioned in *Fig. 1*. All dimensions are in metre (m).

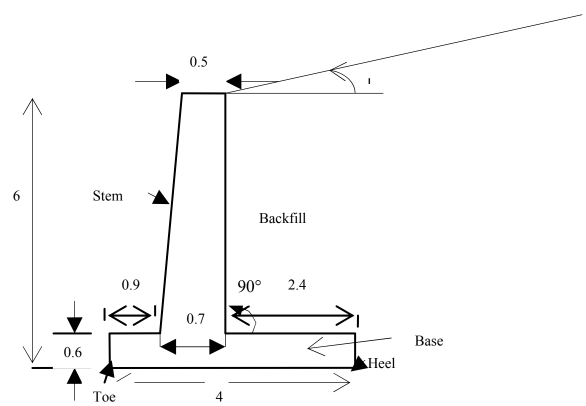

Fig.1. Geometrical parameters of cantilever retaining wall

Material properties for the model are as follows
Backfill: $\varphi = 35°$ for $\gamma = 19.6$ kN/m^3, E = 255 kPa, $\mu = 0.3$
Foundation: $\varphi = 40°$ for $\gamma = 19.6$ kN/m^3
Reinforced concrete: $\gamma = 23.6$ kN/m^3, E = 25GPa, $\mu = 0.15$
Interface element: $k_s = 3.3e5$ kPa and $k_n = 3k_s = 9.9e5$ kPa
$\delta = 26.6°$, $\iota = 0°, 10°, 20°$
where, φ is the internal friction angle, δ is the friction angle between wall face and soil, γ is the unit weight, ι is the angle of inclination of backfill with horizontal, E is elastic modulus, μ is poisson's ratio, k_s is the tangential or shear stiffness and k_n is the normal stiffness.

Elements Used

Higher order 2D elements having quadratic displacement behavior are used to mesh the geometry. Meshing of interface is done using 3 node surface-to-surface contact elements.

Boundary Conditions

Boundary conditions for the retaining wall – soil system are

Backfill: The artificial boundary is put at 2.5 times the height of wall towards the heel side and equal to the height of wall towards toe side. Movement is restrained in horizontal direction on both sides.

Foundation: Soil is modelled to a depth of 0.5 times the height of wall and the movement is restrained in both directions, namely horizontal and vertical.

STATIC RESPONSE

Modeled as Continuum

While modeling the retaining wall in continuum with backfill and foundation soil, the elements constituting the wall and soil are connected through same node. This prevents relative motion between wall and soil boundary, thereby the deflection and stresses are same at the corresponding points. This is obviously not the actual case, but the modeling is done here to show the variation of response with modeling as continuum with modeling with soil-structure interface (presented later). It is to be noted that even though the model does not have any interface friction, it is not the case of Rankine's frictionless model. Deformed meshes for different values of ι are presented from *Fig.2 to Fig.6.* Active earth pressure coefficients and point of application evaluated from these analyses are presented in Table2.

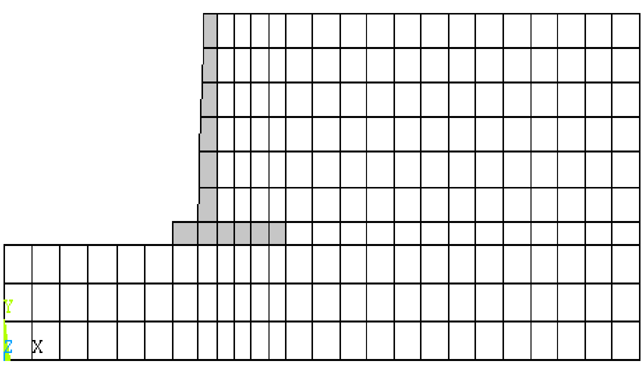

Fig.2. FE Mesh for a continuum model

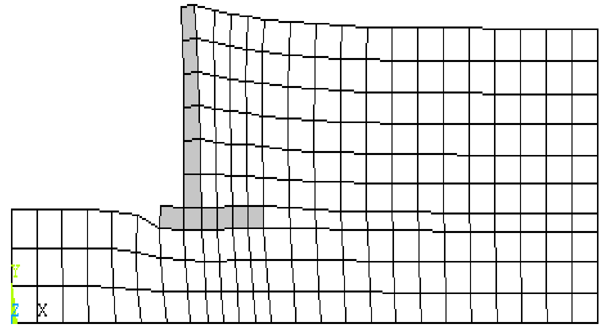

Fig.3. Deformed mesh for ι=0°

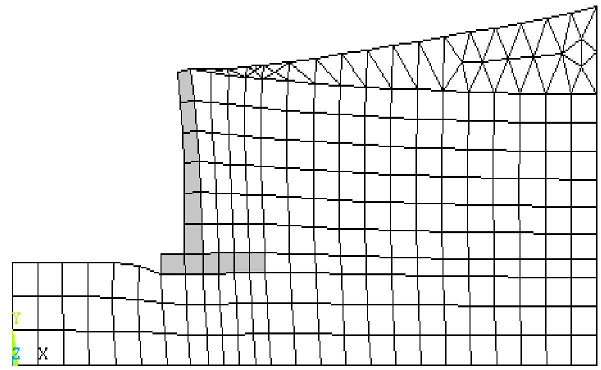

Fig.4. Deformed mesh for ι=10°

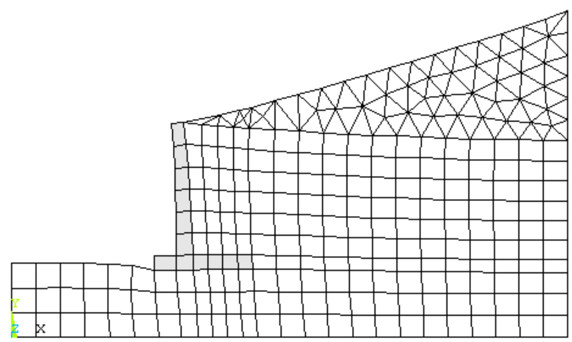

Fig.5. Deformed mesh for ι=20°

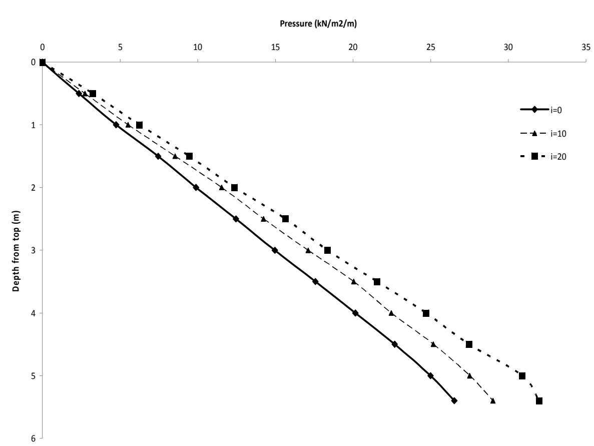

Fig.6. Lateral active pressure distribution for varying ι

Table 1. Total active force and point of application

ι (degrees)	K_a	Total Active Force (kN/m)	Ratio of point of application above base to the length
0	0.245	78.017	2.04
10	0.294	101.775	2.29
20	0.321	116.123	2.45

<u>Modeled with Interface</u>

Now the wall is modeled with allowance for slip and separation between the two surfaces by using contact element with properties mentioned earlier. The normal and tangential stiffness values used for modeling the interface are determined from iterative procedure [Saxena, 2009] for a coefficient of friction of 0.5. Deformed meshes for different values of ι are presented from *Fig.7 to Fig.10.* Active earth pressure coefficients and point of application evaluated from these analyses are presented in Table2.

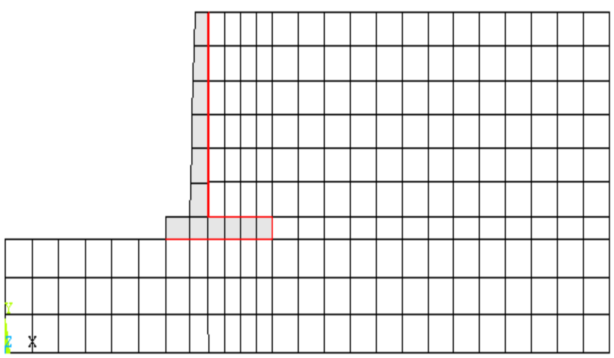

Fig.7. FE Mesh for a model with interface

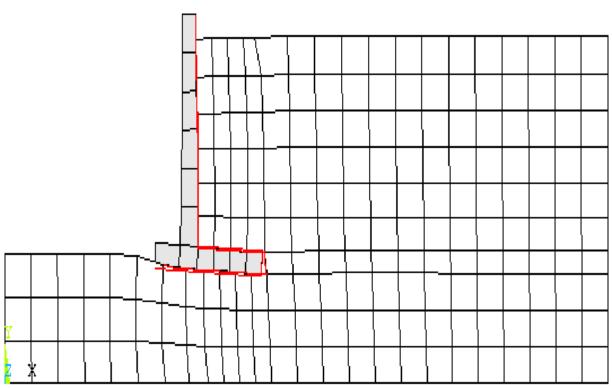

Fig.8. Deformed mesh for ι=0°

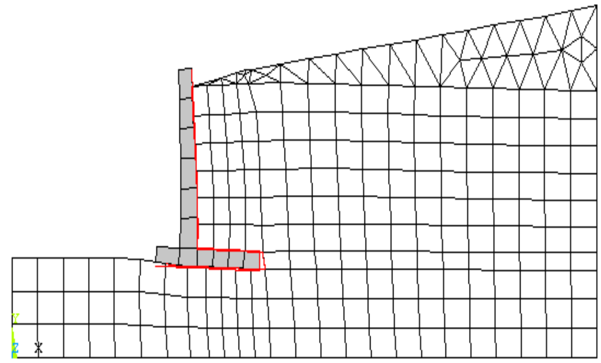

Fig.9. Deformed mesh for ι=10°

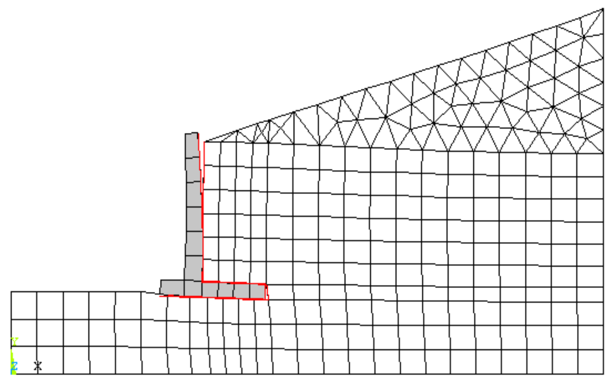

Fig.10. Deformed mesh for ι=20°

Table 2. Total active force and point of application

ι (degrees)	K_a	Total Active Force (kN/m)	Ratio of point of application above base to the height
0	0.241	68.7825	0.35
10	0.275	77.123	0.39
20	0.312	93.555	0.4

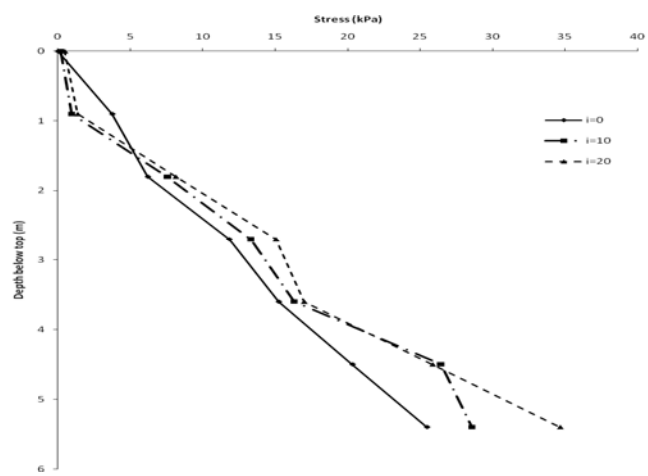

Fig.11. Lateral active pressure distribution for varying ι

Comparison charts have been drawn between the three cases for varying backfill angle.
1. Theoretical analysis
2. FEA with wall-soil modeled as continuum
3. FEA with interface modeled

It can be observed that compared to theoretical analysis, the stresses calculated from FE analysis for continuum is slightly more, while that with interface are comparatively less. This reduction can be attributed to the freedom being provided to separate and slipping, thereby increasing the displacement which leads to relaxation in stresses.

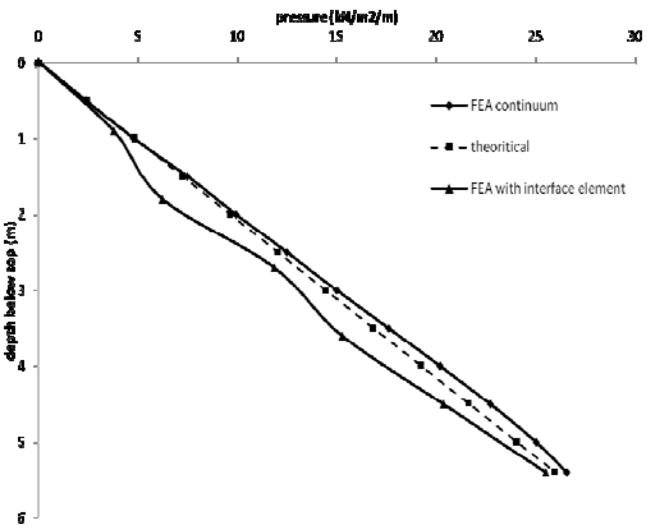

Fig.12. Lateral Stress Comparison plot for ι = 0°

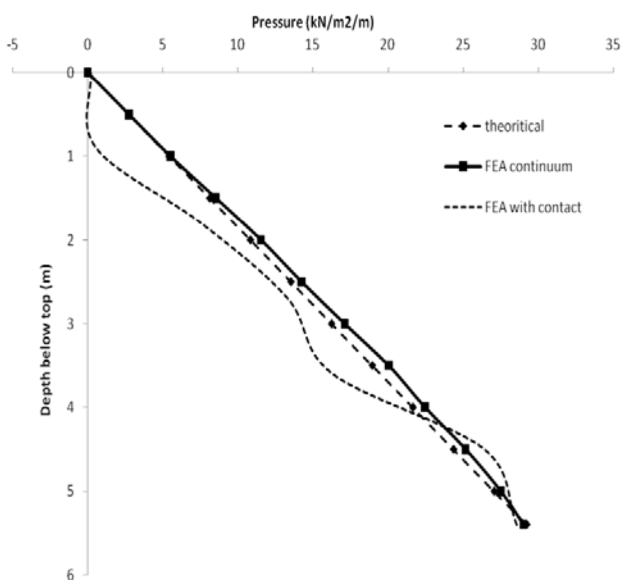

Fig.13. Lateral Stress Comparison plot for ι = 10°

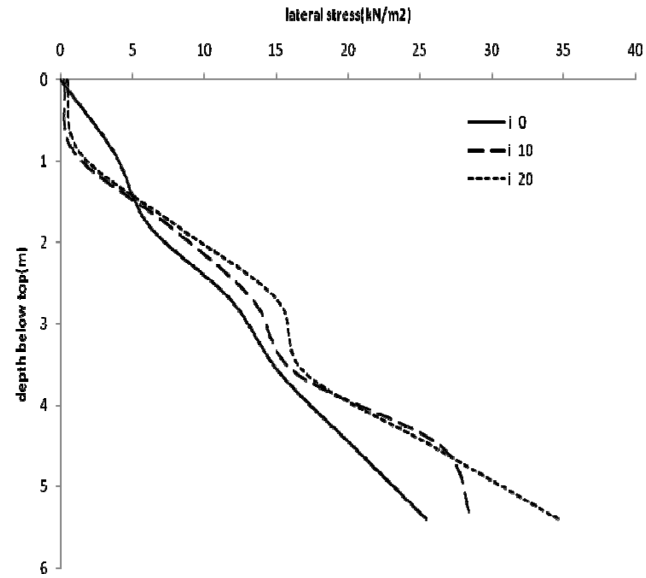

Fig.14. Lateral Stress Comparison plot for ι = 20°

SEISMIC RESPONSE

For the model with backfill angle, ι = 0° and 20°, seismic transient analysis was done for both the cases, i.e., with and without interface. Free vibration analysis was done to estimate the frequencies of vibration for first three modes. These values are used to calculate the Rayleigh damping parameters. Newmark's implicit time integration scheme is used by the software to solve the equation. A time stepping of 0.02 seconds with time sub-stepping of 0.001 sec is used for transient analysis.

Input Earthquake Motion

20th October, 1991 Uttarkashi earthquake motion data has been applied to the retaining wall-soil system. The earthquake motion has a PGA of 0.242g or -2.372 m/sec^2. Duration of recorded time history of the motion is 40 seconds. As most of the peaks occurred within 20 seconds of the motion, time history of that much motion, *Fig.15*, is used for study. To get significant slip and separation, the acceleration values have been multiplied by a factor of 1.5.

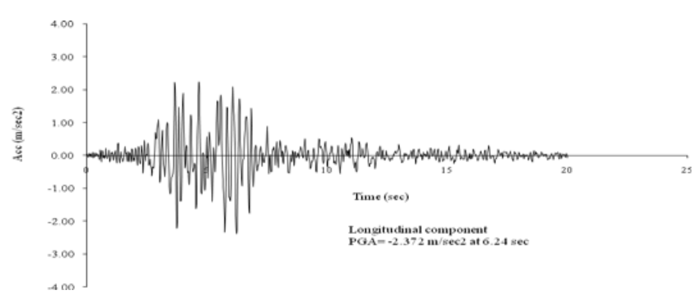

Fig.15 Input Time History

Free Vibration Response

Free vibration analysis was done to estimate first three predominant periods. Analysis was done for three cases

1. Retaining wall only,
2. Retaining wall + soil, modeled as continuum, and
3. Retaining wall + soil, with interface modeled.

Time period of first three modes for the mentioned cases are tabulated in Table3 and plotted in *Fig.16*.

Table 3. Time Period of first three modes

Mode	**Retaining Wall**	**Retaining Wall + Soil (as continuum)**	**Retaining Wall + Soil (as discontinuous)**
1	0.079745	0.126263	0.12734
2	0.01526	0.104167	0.105152
3	0.006664	0.085034	0.086505

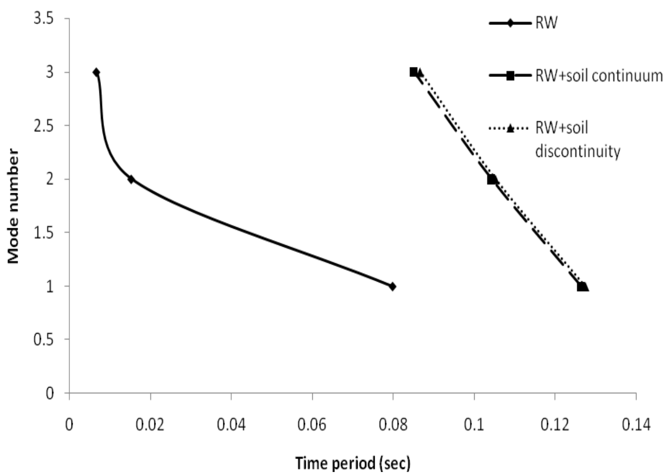

Fig.16 Time period plot

We can observe that wall-soil interaction system is much more flexible than that the wall fixed at base and hence justifies the importance of inclusion of soil.

Rayleigh Damping

Rayleigh damping is used for the dynamic analysis of this system. Alpha damping and Beta damping are used to define Rayleigh damping constants α and β. The damping matrix (C) is calculated by using these constants to multiply the mass matrix (M) and stiffness matrix (K).

$$(C) = \alpha(M) + \beta(K) \quad (1)$$

The values of α and β are not generally known directly, but are calculated from modal damping ratios, ξ_i. ξ_i is the ratio of actual damping to critical damping for a particular mode of vibration, i. If ω_i is the natural circular frequency of mode i, α and β satisfy the relation

$$\xi_i = \alpha/2\omega_i + \beta\omega_i/2 \quad (2)$$

The values of α and β used are taken as for equivalent damping ξ = 10%. First two modes are considered to calculate the value of constants.

Material Properties

The coefficient of friction between wall and soil is assumed to be 0.5, i.e. δ = 26.6°. Backfill and foundation soil are assumed to have same internal angle of friction, □ = 35°. The tangential or shear stiffness k_s = 3.3e5 kPa and The normal stiffness $k_n = 3k_s$ = 9.9e5 kPa

RESULTS

The displacement responses for ι = 0° and 10° have been calculated and plotted as shown in Figs 17 to 24. The peak Ux response at top of RW is higher in case of contact model (model with interface) rather than for continuum model.

Displacement Response at Top of Wall for ι = 10°

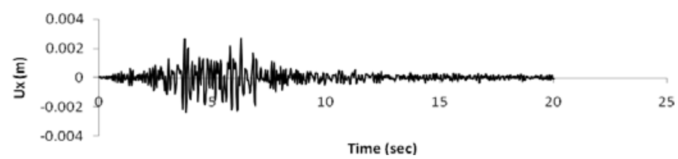

Fig.17 Ux at top of RW modeled as continuum with backfill

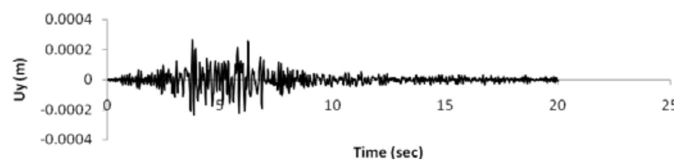

Fig.18 Uy at top of RW modeled as continuum with backfill

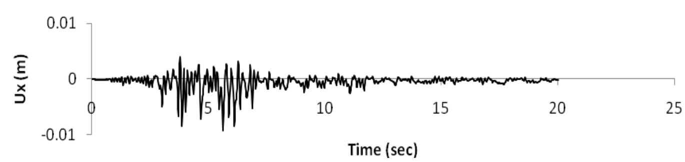

Fig.19 Ux at top of RW modeled with interface with backfill

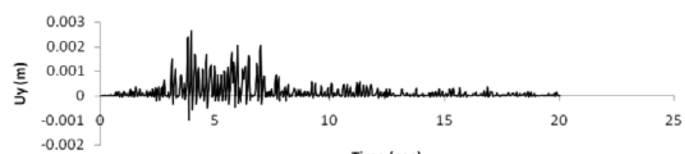

Fig.20 Uy at top of RW modeled with interface with backfill

Displacement response at bottom of heel slab for ι = 0°

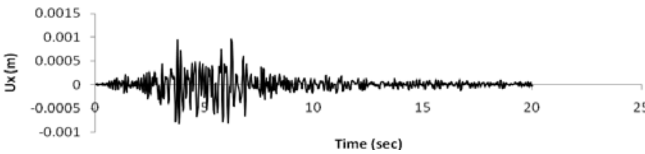

Fig.21 Ux at bottom of heel of RW modeled as continuum with backfill

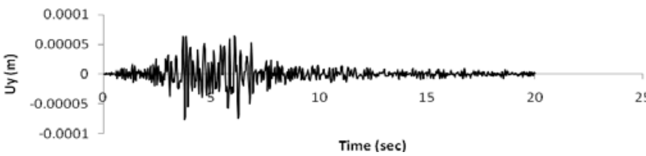

Fig.22 Uy at bottom of heel of RW modeled as continuum with backfill

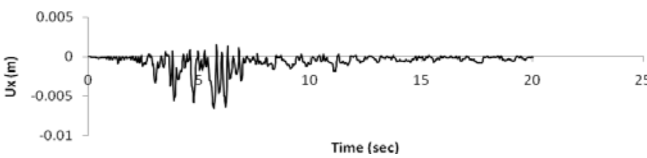

Fig.23 Ux at bottom of heel of RW modeled with interface

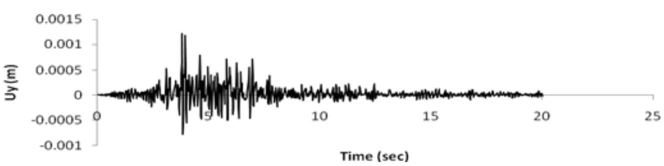

Fig.24 Uy at bottom of heel of RW modeled with interface

The stress responses for ι = 0° and 10° have been calculated and plotted as shown in Figs 25 to 28. The peak Sx response at top of RW is lower in case of contact model (model with interface) rather than continuum model.

Stress response at mid-height of stem for ι = 0°

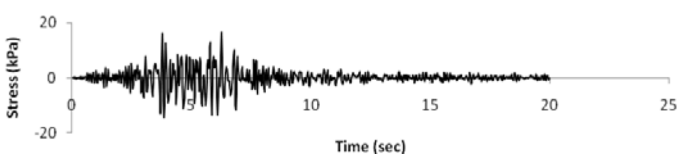

Fig.25 Sx for RW modeled as continuum with backfill

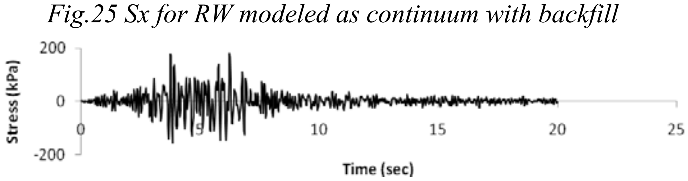

Fig.26 Sy for RW modeled as continuum with backfill

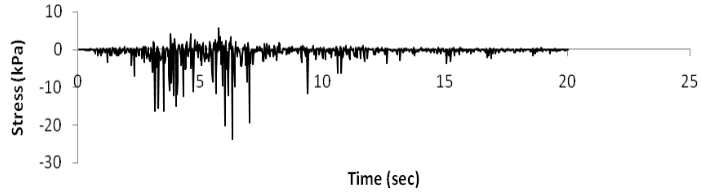

Fig.27 Sx for RW modeled with interface

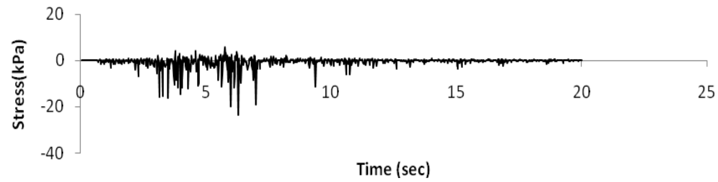

Fig.28 Sy for RW modeled with interface

The peak displacement and stress response have been presented in tabular form in Table-4 and Table-6 and compared for continuum and contact model. Values of slip and separation have been evaluated using displacement peaks and are shown in Table-5 and Table-7.

Table 4. Comparison of Peak Displacement Response for ι = 0°

Response point	**Continuum model**		**Contact model**			
			Wall		**Corresponding soil**	
	Ux (mm)	**Uy (mm)**	**Ux (mm)**	**Uy (mm)**	**Ux (mm)**	**Uy (mm)**
Top of wall (time in sec)	2.69 (6.24)	0.22 (6.24)	8.51 (5.62)	2.39 (3.96)	1.31 (5.62)	1.36 (3.96)
Bottom of heel slab (time in sec)	0.758 (6.24)	0.08 (3.76)	6.10 (6.2)	1.00 (3.96)	0.18 (6.2)	0.58 (3.96)
Bottom of toe slab (time in sec)	0.93 (6.24)	0.57 (3.76)	6.10 (6.2)	0.30 (3.96)	0.04 (6.2)	0.22 (3.96)

Table 5. Slip and Separation for ι = 0°

Response point	Slip (mm)	Separation (mm)
Top of wall	0.46	6.3
Bottom of heel slab	5.92	0.42
Bottom of toe slab	6.06	0.08

Table 6. Comparison of Peak Displacement Response for ι = 20°

Response point	Continuum model		Contact model			
			Wall		Corresponding soil	
	Ux (mm)	Uy (mm)	Ux (mm)	Uy (mm)	Ux (mm)	Uy (mm)
Top of wall (time in sec)	2.73 (3.78)	0.27 (3.78)	9.27 (5.62)	2.64 (3.96)	1.81 (5.62)	1.93 (3.96)
Bottom of heel slab (time in sec)	0.76 (4.66)	0.11 (6.24)	6.61 (5.66)	1.21 (3.82)	0.18 (6.2)	0.68 (3.96)
Bottom of toe slab (time in sec)	0.95 (3.78)	0.60 (3.78)	6.62 (5.66)	0.63 (3.96)	0.04 (6.2)	0.32 (3.96)

Table 7. Slip and Separation for ι = 20°

Response point	Slip (mm)	Separation (mm)
Top of wall	0.71	7.46
Bottom of heel slab	6.43	0.53
Bottom of toe slab	6.58	0.3

Dynamic Increment Plot

Dynamic increment, which is the difference between dynamic response and static response, gives us a quantitative indication of how displacements and stresses increase when subjected to seismic conditions. Stress response vs depth plots for different static and dynamic cases are shown in Fig.29 to Fig.32. Difference between the two response profile indicates the dynamic increment. Stress time history is plotted at a height of 2.7m above the top of heel slab which is mid-height of stem wall. Stress in soil at the instant when stress in wall is maximum, is mentioned and a dynamic increment plot at that instant along the height of stem wall is plotted. At the same instant the stress at 3.6m height above heel top is at maximum. Another plot for dynamic increment is drawn at 5.62 sec. At this instant, stress is maximum at 1.8m height above the heel base, i.e. 2.4m above base of wall, which is 0.41 times the height of wall. Similar plots have been drawn for ι = 0°. Maximum dynamic increment values for Fig.29 to 32 are 10 kPa, 7 kPa, 12 kPa and 15 kPa respectively .

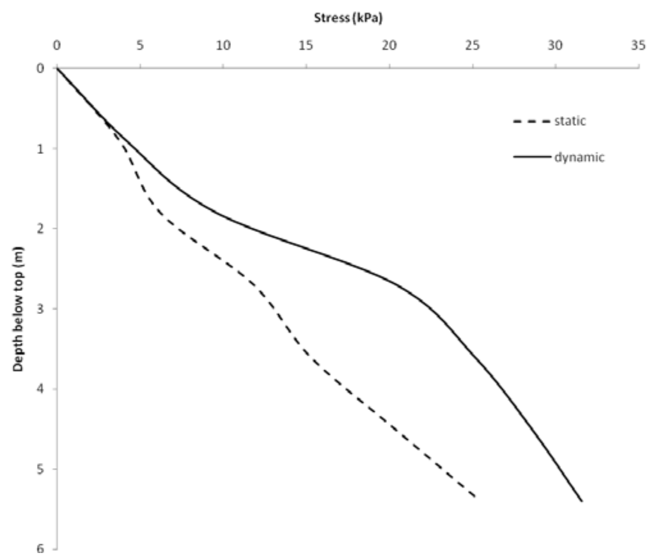

Fig.29 Dynamic increment plot for ι = 0° at 6.28 sec

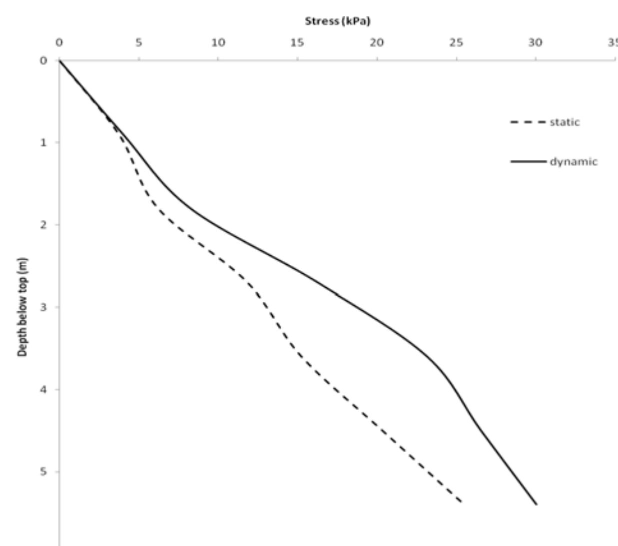

Fig.30 Dynamic increment plot at for ι = 0° at 5.62 sec

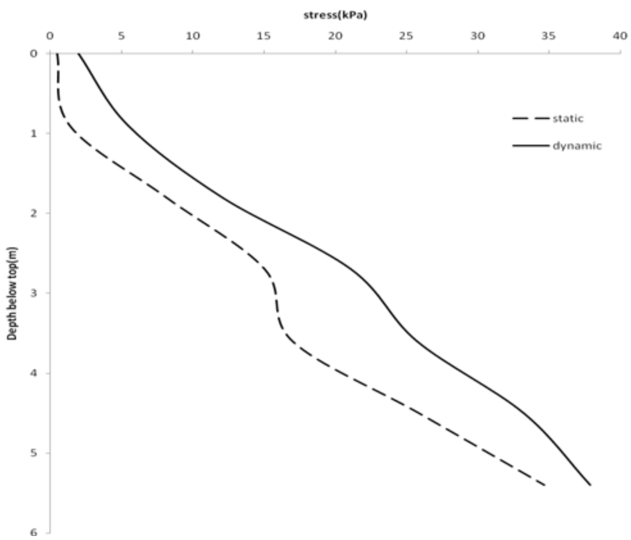

Fig.31 Dynamic increment plot for ι = 20° at 6.21 sec

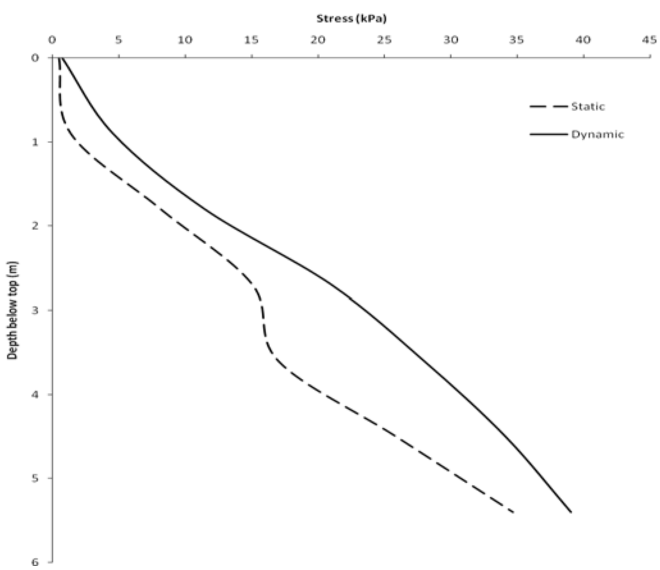

Fig.32 Dynamic increment plot for ι = 20° at 5.62 sec

CONCLUSIONS

A study of dynamic earth pressure on concrete retaining wall has been made where a retaining wall having L/B ratio of 1.5 with different angle of inclination of backfill is taken as an example. Modeling of the retaining wall and soil is done with 8-noded quadratic element, 6-noded triangular element and 3-noded contact element. The conclusions derived are as following:

- For backfill angle ι = 20°, the factor of safety against sliding for static case is 1.77, which is just greater than the recommended value of 1.5. For seismic conditions it is 0.88 which lesser than the static case.
- The response is obtained for Uttarkashi earthquake motion (20 sec). A maximum separation of 6.3mm at 5.62 sec at the top of wall is observed and a maximum slip of 0.46 mm at 3.96 sec at the top of wall is observed.
- It is found that the dynamic earth pressure is more than static earth below 1.0 m from the top of the wall. Also the maximum value of dynamic earth pressure is about 1 to 1.7 time more than the static earth pressure.
- The displacement response of retaining wall significantly changes with the introduction of interface. When interface movement is allowed the retaining wall move in outward direction which is the realistic situation.

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