Uncertainties of Shear Forces and Bending Moments in Retaining Wall Due to Earthquake Loading

Vidhi Rasik Solanki, Prajakta Jadhav and Amit Prashant

Abstract The section design of a cantilever retaining wall stem requires factored shear forces and bending moments. Conventional design philosophies have adopted pseudostatic force based approach for the design of wall stem under seismic loading. This approach depends upon the selection of a suitable horizontal seismic coefficient (k_h). The primary aim of this study is to develop understanding of the uncertainties involved with respect to this seismic coefficient. A non-linear finite element model of cantilever retaining wall placed on medium dense sand has been developed in GiD and dynamic analysis has been performed in OpenSees. Four different earthquake motions with peaks concentrated over a certain time interval and peaks distributed for a larger duration of time have been selected for the analysis. These ground motion records have been scaled to 0.36 g PGA consistent with zone V. The forces and moments computed from dynamic analysis have been compared with those calculated using conventional pseudostatic force based methodologies to understand the influence of inappropriate selection of k_h value in design. Also, the uncertainty involved with respect to the location of the point of action of the dynamic increment has also been studied. The influence of this uncertainty has been reflected in the prediction of design moments. The study aims to evoke the need for modification in the current design philosophy which can efficiently capture these uncertainties with respect to seismic loading.

Keywords Cantilever retaining wall · Pseudostatic force based approach · Horizontal seismic coefficient · OpenSees · Uncertainties

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1 Introduction

The conventional design methodology for seismic design of cantilever retaining wall approximates the complex and dynamic earthquake forces into a single pseudostatic force of $k_h W$ where k_h is the horizontal seismic coefficient and W is the weight of the triangular soil wedge behind the wall [1, 2]. Uncertainty in the value of k_h leads to unreliable calculation of shear forces which gets carry forwarded in the calculation of bending moment with an additional uncertainty in the location of the moment arm of the static and dynamic increment component of the seismic lateral earth pressure. Various studies in the literature have proposed values for k_h [3, 4] and also values for point of application of the seismic active thrust [5–7]. The primary aim of this paper is to make the readers aware of the uncertainties that need to be dealt with while designing for seismic forces and to evoke the need for modifying the current design philosophy to capture these uncertainties and incorporate them in the seismic design of cantilever retaining walls.

The accuracy with which the pseudostatic force is calculated depends on the accuracy in calculation of the variables involved such as soil density (γ) and k_h. Higher confidence in the value of soil density than in k_h is because of the ease with which numerous experiments could be carried out to determine the actual soil density. Unfortunately, carrying out numerous real-time tests on cantilever retaining walls to be able to predict the seismic forces and moments acting is tedious and impractical leading to higher uncertainty in the value of k_h. Bray et al. (2008) suggested that k_h lies between PGA/g and 0.5 PGA/g where PGA is the Peak Ground Acceleration. A study by Kolay et al. [4] has proposed that k_h equals PGA up to 0.45 g PGA and for PGA greater than 0.45 g, k_h assumes a constant value of 0.45. Atik and Sitar [8] have proposed a correlation between coefficient of dynamic increment earth pressure (ΔK_{AE}) and PGA. Other studies [9, 10] have also proposed equations for k_h which depend on PGA as well. Codal provisions by Australia [11] and New Zealand [12] suggest the use of k_h as a_{max} and 0.5 a_{max} depending on the deformation allowed. There is a need to identify and at the same time, mathematically quantify the uncertainties related to the value of k_h.

Several different recommendations for the point of application of the static (H_{st}) and dynamic increment component (H_{di}) of seismic active earth pressure in previous studies are an indication of the uncertainty in H_{st} and H_{di}. A study by Seed and Whitman [6] suggests that the static component acts at H/3 while the dynamic increment component acts between 0.6 and 2/3 H from the base of the stem-wall where H is the height of the stem-wall. Elms and Richard [7] suggest rectangular distribution of the total active seismic thrust and hence propose to use H/2 as the point of application of the total lateral seismic pressure. The present design approach, Allowable Strength Design (ASD) does not consider these specific uncertainties as it has only one Factor of Safety (FOS) to provide a reasonable safety margin against uncertainties in both load and resistance [13]. There is a need for an alternate design methodology which provides a quantitative safety margin rather than a factor that depends on experience and judgement [13] or a need for modification in ASD such that it can incorporate the uncertainties and thereby improve its reliability for seismic design of cantilever retaining wall.

Four earthquakes with varying characteristics are scaled to 0.36 g PGA and used as input for dynamic analysis of a cantilever retaining wall. Shear forces and bending moment measured at the bottom of the stem-wall were obtained as the output results and were calculated using the Mononobe–Okabe method [1, 2] henceforth referred to as M-O method. The k_h values were back-calculated by comparing the measured and calculated shear forces and bending moments. Taking the values recommended by Kolay et al. [4] for k_h and by Seed and Whitman [6] for H_{st} and H_{di} as baseline, the variation in back-calculated k_h and in H_{st}, $H_{di,}$ respectively, has been analysed.

2 Model Description

A finite element model of cantilever retaining wall has been redeveloped in GiD and analysed in OpenSees in accordance with Kolay et al. [4]. The wall of height 12 m is retaining a horizontal soil mass of loose sand and is placed on medium dense sand. The domain simulated is 260 m long and 38 m deep. The details of the same are as shown in Fig. 1. The wall has been modelled using linear elastic beam-column elements of size 0.5 m. The soil mass has been modelled using quad elements and has been assigned properties corresponding to pressure-dependent multi-yield model. In

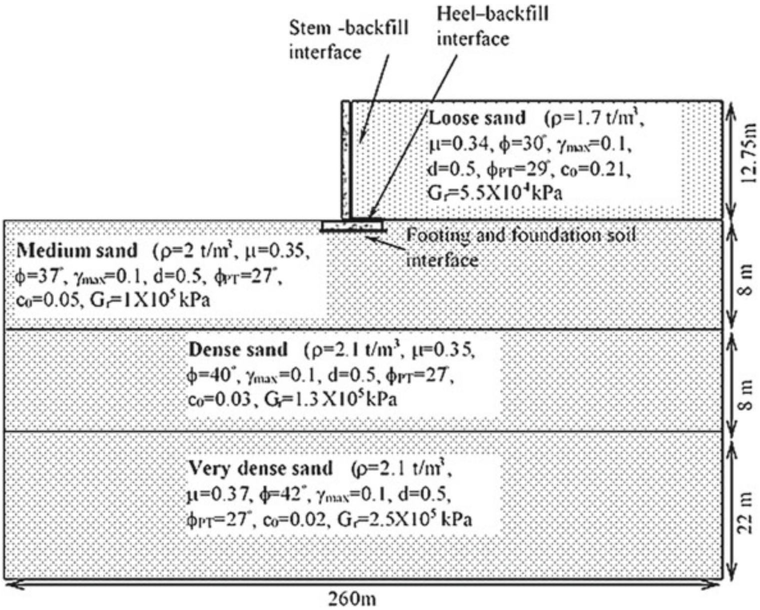

Fig. 1 Schematic diagram of computational model

order to consider slippage along the interfaces of wall with soil, three interfaces, viz, stem–backfill interface, SBI, heel–backfill interface, HBI, and footing–foundation–soil interface have been modelled in accordance with Kolay et al. [4].

3 Uncertainties Due to Earthquake Motion

Each earthquake characteristic has its own unique impact on the seismic behaviour of a structure. The values of k_h recommended in literature suggest that it is based only on the PGA of the earthquake, indirectly ignoring the effects of other earthquake characteristics such as duration of the earthquake, bracketed duration, frequency content and distribution of peak. The two earthquakes shown in Fig. 2, when scaled to the same PGA, will not cause similar forces and stresses in the retaining wall [14]. The earthquakes were scaled to the same PGA so that the effect due to this earthquake characteristic would remain the same for each case and the influence of the other characteristics on the design shear forces and bending moments is highlighted.

Four earthquakes were chosen from PEER database and their acceleration time histories were obtained. The selection was such that all the four earthquakes had varied characteristics as shown in Table 1. The acceleration time histories were scaled using SeismoSignal and the scaled velocity time histories were used as input

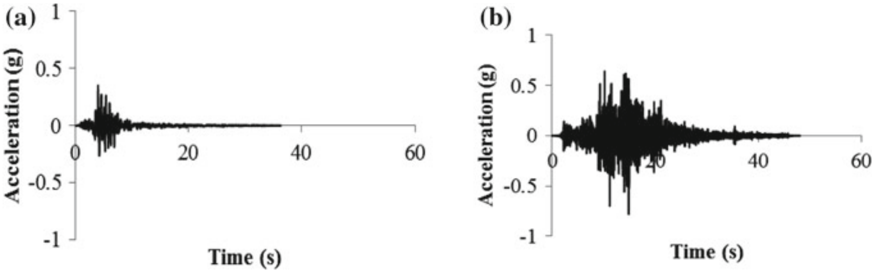

Fig. 2 Acceleration time histories of **a** Friuli and **b** Landers earthquakes (PEER)

Table 1 Characteristics of earthquakes chosen for dynamic analysis of cantilever retaining wall

Sr No	PGA (g)	Total duration (s)	Bracketed duration (s)	Peak distribution	Predominant period (s)
1	0.34	27	18.27	Distributed, wide peaks	0.28
2	0.78	85	33.33	Distributed	0.08
3	0.19	14	3.16	1 concentrated peak	0.28
4	0.40	15	14.21	5 concentrated peaks	0.38

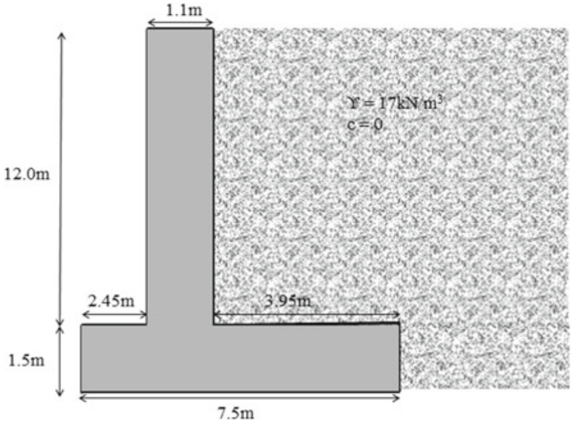

Fig. 3 Geometry of the cantilever retaining wall and soil parameters

to the dynamic analysis. The geometry of the cantilever retaining wall on which the dynamic analysis was performed is shown in Fig. 3. Shear force and bending moment at the base of the wall stem were obtained from analysis results.

The M-O method is one of the oldest methods in practice and provides a reasonable estimate of the seismic lateral earth thrust till date [1, 2]. Shear force is calculated by adding the seismic lateral earth pressure and $k_h W_{stem}$ where W_{stem} is the weight of the wall stem. Here, the seismic coefficient to be multiplied with W_{stem} is assumed to be k_h for the sake of simplicity and homogeneity [4]. Values for k_h as recommended by Kolay et al. [4] are used for shear force calculation. Bending moment is calculated by assuming that H_{st} is H/3, H_{di} is 0.6 H [6] and the wall seismic force acts at 0.5 H. The output shear force and bending moment values were located on their respective M-O curves in Fig. 4 and corresponding k_h values were noted. Henceforth, these k_h values will be referred as back-calculated k_h values. Also, values of H_{st} and H_{di} were calculated from static and dynamic increment stresses obtained from dynamic analysis, respectively. The M-O curves could be reproduced using the soil parameters mentioned in Fig. 3.

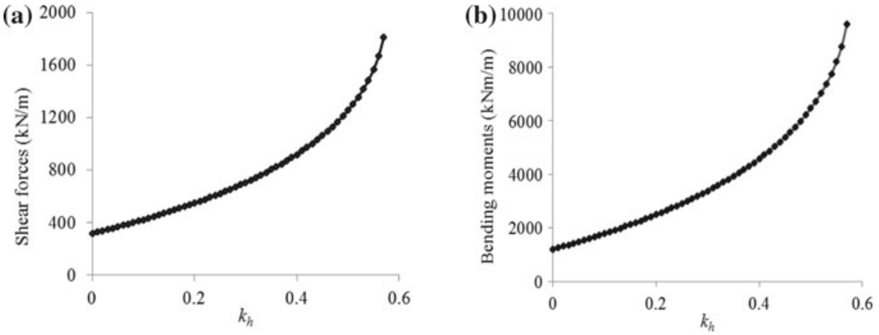

Fig. 4 M-O curves for **a** shear force and **b** bending moment for given wall geometry

4 Interpretations of the Uncertainties Observed

The calculated values of shear force and bending moments and those computed from dynamic analysis for the four earthquakes are shown in Table 2. As per Kolay et al. [4] recommendation, the value of k_h should be taken as 0.36 for all the four earthquakes and thus the design shear force would be 826 kN/m for each case. The design bending moment using Seed and Whitman [6] recommendation would be 4479 kNm/m. The computed values for both shear force and bending moment are significantly different from the calculated ones with computed shear forces ranging from 581 to 955 kN/m and computed bending moments ranging from 2341 to 4389 kNm/m. Similar conclusions can also be made about the back-calculated k_h values as shown in Table 3. The back-calculated k_h values for shear force range from 0.22 to 0.42 while those for bending moment range from 0.18 to 0.39. The recommendation by Kolay et al. [4] and that by Seed and Whitman [6] would sometimes underpredict and sometimes overpredict the actual shear forces and bending moments, respectively, leading to anything between unsafe to oversafe design using ASD. The use of a single value for k_h, H_{st}, and H_{di} as per previous studies will lead to unpredictable shear forces and bending moments unless over-conservative values are used leading to uneconomic designs. There is a need to account for this significant variation in the measured forces and moments in the design methodology used.

All the four analyses have shown that the static component acts at 0.28 H from the stem base which is lower than H/3 as per the assumption that the static stresses follow triangular distribution [6]. The value of H_{di} ranges from 0.41 to 0.57 H from the bottom which clearly signifies the uncertainty in the location of the dynamic

Table 2 Computed and predicted shear forces and bending moments

EQ No	Shear force computed from dynamic analysis (kN/m)	Calculated shear force (kN/m)	Bending moment computed from dynamic analysis (kNm/m)	Calculated bending moment (kNm/m)
1	787	826	3425	4479
2	581	826	2341	4479
3	683	826	3162	4479
4	955	826	4389	4479

Table 3 Obtained values of k_h for shear force, bending moment, H_{st} and H_{di} for four earthquakes

EQ No	k_h for shear force	k_h for bending moment	H_{st} (H)	H_{di} (H)
1	0.34	0.23	0.28	0.46
2	0.22	0.14	0.28	0.57
3	0.29	0.21	0.28	0.50
4	0.42	0.30	0.28	0.41

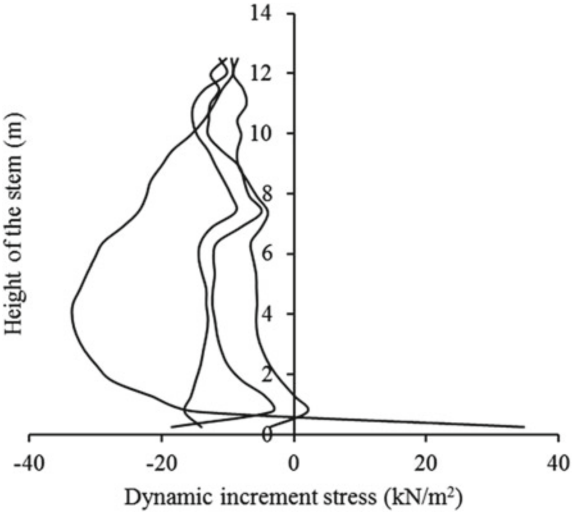

Fig. 5 Stresses in the stem-wall due to the dynamic increment component

increment component. The plot of the dynamic increment stress along the height of the stem-wall at the instant when the dynamic increment stress is the highest is shown in Fig. 5. The dynamic stress distribution obtained from analysis does not necessarily follow a linear or rectangular distribution as suggested by previous studies. Even if only four earthquakes are taken, the distribution is triangular for earthquake 4, rectangular for earthquake 2 and rectangular distribution with a kink in the mid-upper portion for earthquakes 1 and 3. The dynamic stress distribution varies depending on the earthquake characteristics. Figure 5 shows that the approximate location of the dynamic increment component lies somewhere around the wall mid-height. Higher variability in H_{st} and H_{di} can significantly affect the calculation of bending moments and thus need to be addressed in the design methodology used.

The calculation of unfactored shear forces and bending moments itself encompasses so many uncertainties that multiplying them with a factor of safety does not necessarily yield safe and reliable design. It is not feasible to comment how much safe or how much unsafe the design actually is. Since ASD has been in practice for years and its usage being simple, it would be extremely difficult to replace it with some other design philosophy which could identify and quantify the uncertainties. Therefore, there is a pressing need to modify certain parameters in ASD such that they capture the uncertainties and affect the design accordingly.

5 Conclusions

It is nearly impossible for two earthquakes to produce the same amount of impact on a structure. The variation in the back-calculated values of k_h and the calculated values of H_{st}, H_{di} clearly depict the complexity involved in determining the actual forces and moments produced in the structure. Recommendations from previous studies such as that by Kolay et al. [4] for the value of k_h and Seed and Whitman [6] for H_{st} and H_{di} tend to sometimes produce safe while sometimes over-conservative design. The use of FOS in ASD does not provide the designers with a quantitative margin of safety. Since some of the sources of uncertainties are identified, it is necessary to figure out ways that can be used to capture these uncertainties. Despite its limitations, owing to the simplicity in the current approach, conventional design approach can still be adopted by engineers incorporating the aforementioned uncertainties.

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