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DEVELOPMENT AND EVALUATION OF RESPONSE SPECTRA FOR GORKHA EARTHQUAKE GROUND MOTION AND USING IT TO DETERMINE SEISMIC RESPONSE OF TYPICAL RC BUILDING

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Abstract

The response spectrum, a widely accepted concept used to estimate the lateral forces on the structure, is an envelope of the maximum response of a single degree of freedom (SDOF) system to a particular ground excitation. Since it is very much ground motion dependent and is irregular, it cannot be used directly and has to be smoothed out. It can be used readily to analyse new structures' seismic response and estimate existing structures' response. This study considers 19 ground motion records of 2015 Gorkha Earthquake sequence. These are categorized by magnitudes for rock sites in Kathmandu Valley using Newmark-Beta time stepping method implemented in Python, where elastic response spectra were computed and median and 84.1th percentile design spectra developed. Comparison with the design spectra of the Nepal Building Code (NBC 105:2020), Indian Standard (IS 1893:2016) showed that Gorkha Earthquake (GEQ) based spectra for larger magnitudes ($M_w > 6$) exceeded the code values in the displacement-dominated period range ($T > 2s$). Practical implications were evaluated through the analysis of a typical RC building in ETABS. The seismic demand computed using the GEQ-based spectra, in terms of base shear, story displacement, and inter-story drift, is significantly lower compared to that of code based spectra.

Keywords: Gorkha earthquake; Response spectra; Newmark method; Building codes; Base shear

1. Introduction

Nepal lies in one of the most seismically active regions due to its position on the active Himalayan collision zone. The ongoing subduction of Indian plate under the Eurasian plate results the build-up of huge strain energy released in disastrous earthquakes. Some of the disastrous seismic events that hit this country include the highly destructive Gorkha Earthquake of 2015(Mw 7.8-7.9) , the 1988 Udayapur Earthquake, and the Bihar-Nepal Earthquake of 1934 (Mw 8.0).

The Gorkha Earthquake and its major consequences, including the Mw 7.3 earthquake of May 12, 2015, was the ultimate and awful lesson on how vulnerable this region is with respect to seismic damage. These events led to massive structural destruction, almost 9,000 deaths and displacement of millions of people, especially the Kathmandu Valley which is highly populated (Ohsumi et al., 2016).

The devastation brought to light critical gaps in seismic design practices pre-2015 and raised urgent questions regarding the accuracy of the design motion used. The widespread damaged experienced by the engineered structures indicates that the dynamic demands imposed by the major Himalayan earthquake may not be fully captured by the smoothed spectra of building codes.

Therefore, the recorded ground motions from the Gorkha sequence has proven as an invaluable opportunity to go beyond the generic code based estimates. This study uses this unique dataset to develop site specific response spectra, creating a data driven link between actual earthquake shaking and expected performance of structures in Nepal.

The response spectrum has proven useful in earthquake

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engineering which provides peak dynamic response of all possible structures to earthquake ground motions. While building codes worldwide provides a smooth design spectrum for general use, there is significant importance for site specific and event specific response spectra. It takes consideration of the distance to the causative fault, local site conditions as well as regional geology (Chopra, 2017).

The majority of the historical studies in Nepal have been done on the Probabilistic Seismic Hazard Analysis (PSHA) in attempts to delineate seismic hazards on a regional basis, and hardly any research study has been devoted towards the creation of earthquake based response spectra. For instance, Pradhan et al. (2020) created a seismic hazard map of the country indicating Peak Horizontal Acceleration (PHA) ranges between 0.09 g and 0.50 for 500-years return period, where the most hazards are recorded in the eastern and western regions of Nepal. Two other papers have endeavored to work with site-specific evaluations, Bhusal et al. (2022) providing a site-specific hazard assessment of the Dharahara site in Kathmandu by calculating both the PSHA and the ground response analysis and the Adhikari (2023) performing a site response analysis in the Kathmandu Valley and comparing the obtained results with the provisions of the codes.

However, a critical gap remains. The majority of research in Nepal has focused on probabilistic hazard analysis or site amplification. There hasn't been much work done on creating a region specific response spectra from actual recorded strong motions of local earthquakes. The 2015 Gorkha earthquake provided a wealth of recorded data (Takai et al., 2016), however a systematic development of these records into design-oriented response spectra is still needed.

This study seeks to close this gap by creating tripartite response spectra directly from the Gorkha earthquake records. We go beyond PSHA and generic code spectra to produce event specific and magnitude specific response spectra in order to establish a clear connection between the recorded ground motions and their consequences for structural design.

The paper is devoted to the examination of ground motion records of the 2015 Gorkha Earthquake that hit central Nepal significantly. The development of the acceleration response spectra (ARS), the related pseudo-velocity (PSV), and pseudo-displacement (PSD) spectra, based on the recorded ground motion data, is the main goal. Such spectra are necessary to learn how structures behave dynamically during seismic events.

In addition, the resulted spectral data is compared with the seismic design spectra given by the Nepal National Building Code, NBC 105:2020 and IS 1893:2016.

2. Methodology

2.1. Ground Motion Data Selection and Classification

A total of nineteen strong-motion records were selected for this study from the mainshock (Mw 7.8) of the 2015 Gorkha Earthquake, along with several large aftershocks recorded by Takai et al. (2016). While selecting the data, we had to made sure that both larger events ($Mw > 6.0$) to capture strong, near-fault shaking, and moderate events ($Mw < 6.0$) to represent typical regional responses were selected (Li et al., 2016). Ground motions including three components (two horizontal components and one vertical component) were considered and only one horizontal component, N-S selected from the two horizontal components was used. To study how local ground conditions, affect the earthquake motion, we considered the records based on rock site, the KTP station. This helped us understand how the Kathmandu Valley's rock soil amplifies ground shaking. Finally, all three acceleration records were normalized by their Peak Ground Acceleration (PGA) i.e., we divided each record by its maximum acceleration value so that all the ground motions had the same reference level. This step allowed us to compare the overall patterns of shaking without being influenced by differences in their amplitude.

2.2. Development of Gorkha Earthquake Response Spectra

The main part of our study focused on developing site-specific response spectra, which show how much a single-degree-of-freedom (SDOF) system responds to a particular ground motion's performed dynamic analysis to calculate the elastic response of an SDOF system when subjected to each of the selected earthquake records. The governing differential equation of motion.

$$m\ddot{u} + c\dot{u} + ku = -m\ddot{g}(t) \tag{1}$$

A solution of the equation was obtained using the Newmark-β Average Acceleration Method ($\beta = 1/4$, $\gamma = 1/2$), which yields a linear system of elasticity with unconditional stability. A damping ratio of 5%, which is common for RC structures, was considered, and the analysis was carried out over natural periods from 0.01 s to 5.0 s with adequate time step to guarantee numerical precision.

The maximum spectral displacement (S_d), velocity (S_v), and acceleration (S_a) of each system were computed, with

$$S_v = \omega_n S_d, \quad S_a = \omega_n^2 S_d \tag{2}$$

where ω_n is the natural frequency.

All computations and spectral plots were automated using Python (NumPy, Pandas, and Matplotlib), ensuring consistent and reproducible calculations. This method provided the unprocessed data used to construct the displacement (S_d), velocity (S_v), and acceleration (S_a) response spectra.

For every oscillator, the following spectral parameters were derived:

Spectral Displacement (Sd):

$$Sd(T, \xi) = \max |u(t)| \tag{3}$$

Spectral Velocity (Sv):

$$Sv(T, \xi) = \omega_n \times Sd \tag{4}$$

Spectral Acceleration (Sa):

$$a(T, \xi) = \omega_n^2 \times Sd \tag{5}$$

For each selected combination of damping ratio (ζ) and natural period (T_n), we calculated the spectral values using the standard response spectrum formulas. These values formed the spectral response curve, which shows the maximum expected structural response at different frequencies. We repeated this calculation process for all chosen damping ratios and natural periods so that the entire range of possible responses were covered. After computing all the individual response spectra for each earthquake record, we plotted them graphically in a tripartite plot. We prepared separate spectra for each magnitude (greater than 6 and less than 6) to observe how the responses varied between different records, magnitudes and then combined them to obtain median and one sigma spectra to identify the overall trend of structural behavior across the entire dataset on rocky site.

2.3. Generation of Median and One Sigma Response Spectra

After developing individual response spectra for all the selected Gorkha Earthquake records on basis of their magnitude category, we combined them to create representative tripartite spectra that show the overall behavior of the ground motions. Since the records have varying features, given the difference in fault type, distance and site conditions, we employed two statistical tools, the median (50th percentile) and the one-sigma (84.1^{th} percentile) spectra. The median spectrum represents the average degree of shaking anticipated at the site whereas the 84.1^{th} percentile spectrum represents a greater or upper bound of shaking. We calculated both percentile values for each category using Excel, based on the spectral acceleration data from all records resulting in a total four representative response spectra.

2.4. Comparison with Code Based Spectra

These developed Gorkha Earthquake (GEQ) based spectra were then compared with the design spectra from the NBC 105:2020 and IS 1893:2016 .

2.5. Structural Modelling and Analysis

A typical RC building was modelled (Figure 1) to understand the behavior during earthquakes using both code based and GEQ based response spectra. The model was created in ETABS software and used to represent reinforced concrete (RC) building of G+6 storeys. The model included the usual material and structural properties of RC frame used in Nepal as shown in Table 1 and 2.

Table 1: Description of building

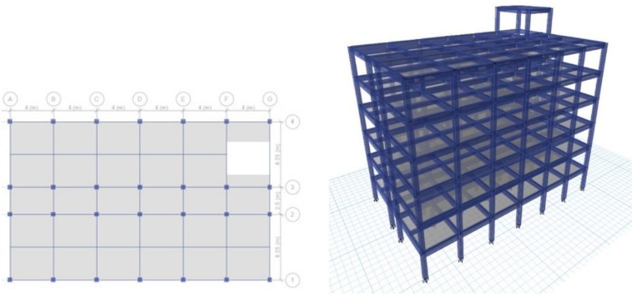
Parameters	Details
Type of Building	School Building
Category of Building	Mid-Rise Building
Structural System	RCC Frame Structure; SMRF
Number of Storey	6 (G + 5 + Staircase Cover)
No. of Bays in X-Direction	6 nos. of Bays
No. of Bays in Y-Direction	3 nos. of Bays
Plinth Area	350.4 m^2
Floor Height	3.3 m
Size of Building	Length = 24 m, Breadth = 14.6 m
Grade of Concrete	M25 for Beam, Column, and Slab
Grade of Steel	Fe500
Type of Beam	Rectangular Beam
Type of Column	Rectangular Column
Type of Foundation	Mat Foundation
Type of Staircase	Dog Legged
Method of Analysis	Dynamic

Table 2: Parameters used for the design of models

Description	**Section / Constant**	**Units**
Column size	400 × 400	mm × mm
Beam size	300 × 525	mm × mm
Secondary Beam size	230 × 400	mm × mm
Slab thickness	120	mm
Specific weight of concrete	25	kN/m^3
Unit weight of brick	19.2	kN/m^3
Modulus of elasticity of concrete	25000	MPa

The model was analyzed, first using the code-based spectra and then using the developed GEQ based response spectra. The difference in results between the analyses helped to understand how much the actual earthquake ground motion affects building performance compared to what is expected by the codes. The following responses were compared for both code-based and GEQ based response spectra:

- Base Shear: This is the sum of horizontal forces at the bottom of the building.
- Storey Displacement: The movement of the top of the building laterally.
- Inter-Storey Drift: This is the difference in movement between two sequential floors that display the extent to which the building sways or bends.



(a) Typical plan of building (b) 3D model of the building

Figure 1: ETABS modelling of the building

3. Results and Findings

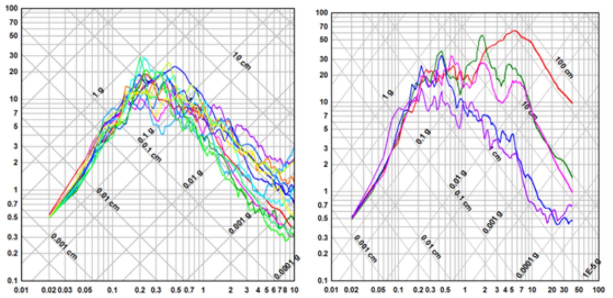
3.1. Characteristics of Developed Response Spectra

The individual, median, and one sigma response spectra derived from the 19 Gorkha Earthquake ground motions are presented. These illustrate the spectral acceleration, pseudo-spectral velocity, and pseudo-spectral displacement across the period range of 0.01s to 50s, for a 5% damping ratio. The variations in spectral shapes and amplitudes across different ground motions, particularly when categorized by magnitude is highlighted.

Figure 2 presents the combined D-V-A spectra, and it can be observed that the ground motions recorded on rocky soil sites in the Kathmandu Valley show significant amplification at certain periods due to local site effects, consistent with previous studies. The response spectra is developed using the Newmark's method are also presented, demonstrating how this statistical approach provides a representative envelope for design from the ensemble of records.

3.2. Comparison of Developed Spectra with Code Provisions

This subsection features comparative graphs, overlaying the four developed GEQ based response spectra with the design spectra prescribed by NBC 105:2020 and IS 1893:2016. Figure 3 indicates the spectral acceleration of GEQ based response spectra is less than that of the design spectra of NBC 105:2020 for all periods for EQ with Mw < 6, however, for EQ with Mw > 6 the GEQ based response spectra exceeds the code based spectra for all the displacement dominated range. Similar observation of the peak spectral acceleration of 0.64g was reported by Dais et al. (2021) which nearly resembles this study peak spectral acceleration of 0.6339g for EQ with Mw > 6 as shown in Figure 3a.



(a) D-V-A plot of earthquake with Mw < 6 (b) D-V-A plot of earthquake with Mw > 6

Figure 2: Combined D-V-A spectra of main and aftershocks of Gorkha earthquake

3.3. Seismic Response of Typical RC Buildings

The study is performed for a typical RC Building through National Building code NBC 105:2020 , IS 1893:2016 and the GEQ based response spectra shown in Figure 4 and 5. The results are then interpreted in terms of the base shear, inter story drift and story displacement.

The base shear is significantly higher from the code-based spectra than from the Gorkha Earthquake (GEQ) spectra. Among the GEQ spectra, the higher the magnitude and percentile level, the higher the base shear. The base shear due to GEQ spectra is 65-85% lower than that specified in NBC 105:2020 and 40-70% lower than that specified in IS 1893:2016. The newer NBC 105:2020 yields higher base shear demands, averaging 58%, than those of IS 1893:2020. Similar observations were made of a nearly 43.5% increase under ULS for NBC 105:2020 compared to IS 1893:2016, as reported by Ghimire and Ranabhat (2025).

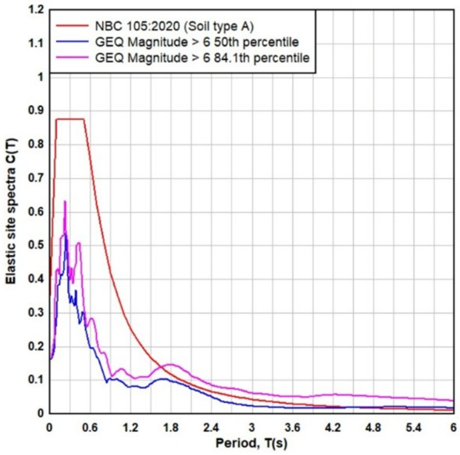
Figure 8 and 9 illustrates the inter-story drift ratio along the height of the building for various spectra. Among all these cases, NBC 105:2020 shows higher drift ratios averaging 57% higher than that from IS 1893:2016 which indicates higher lateral displacement demand due to its higher base shear demand.

In contrast, GEQ spectra shows comparatively smaller drift ratios up to seven times smaller than that of NBC 105:2020 which indicates the actual recorded motions may cause less lateral deformation than code based spectra.

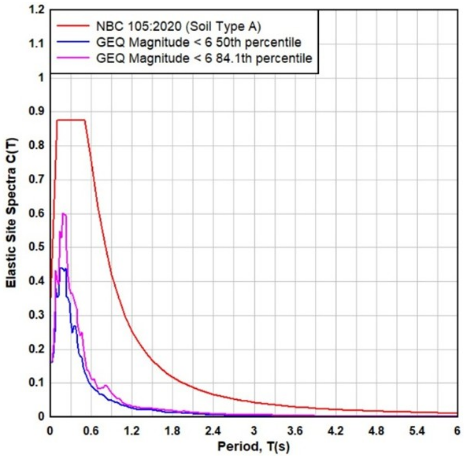
Figure 10 and 11 illustrates the story displacement to the code based spectra as well as GEQ based spectra.

Table 3: Base shear

Spectras	Base Shear in X-Direction(kN)	Base Shear in Y-Direction(kN)
NBC 105:2020	1358.7847	1245.3696
IS 1893:2016	822.9653	823.4695
GEQ Magnitude $<$ 6 for 50th percentile	201.7372	199.8276
GEQ Magnitude $>$ 6 for 50th percentile	398.9308	396.7021
GEQ Magnitude $<$ 6 for 84.1th percentile	273.7318	248.1623
GEQ Magnitude $>$ 6 for 84.1th percentile	482.4317	559.3716



(a)



(b)

Figure 3: Response spectrum curve comparing with NBC 105:2020
(a) GEQ based response spectra of Mw $>$ 6
(b) GEQ based response spectra of Mw $<$ 6

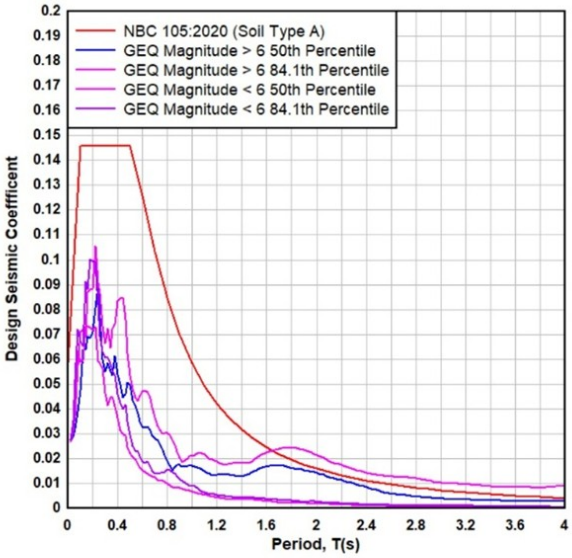


Figure 4: Comparison of design seismic coefficient

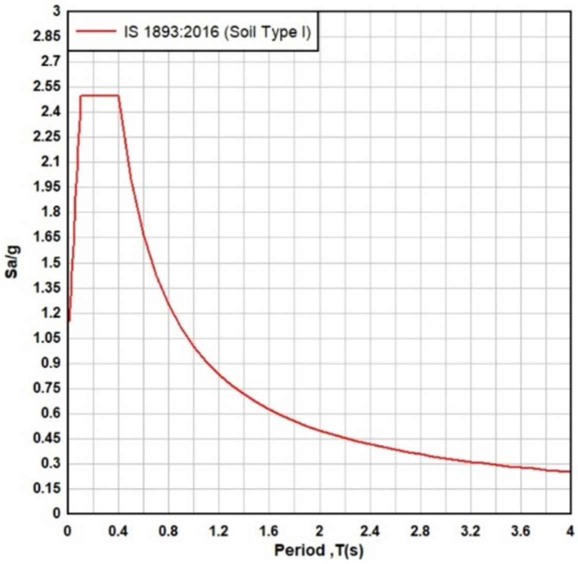


Figure 5: Response spectrum curve IS 1893:2016 (Soil Type I)

This figure also shows that NBC 105:2020 have a higher displacement nearly averaging 57% more than that of IS 1893:2016 which is consistent in having higher shear demand and drift. Similarly, the GEQ based response spectra shows lesser displacement demand than that of the

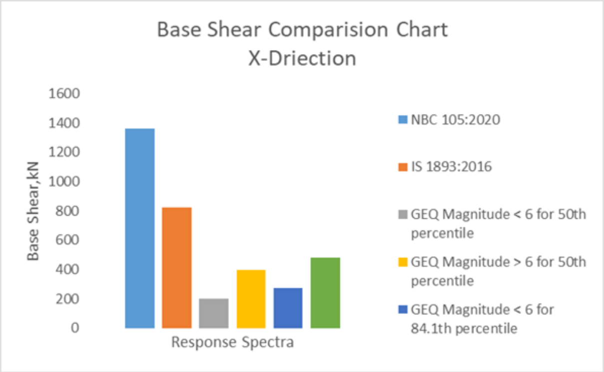


Figure 6: Inter story drift in X-direction from RSM

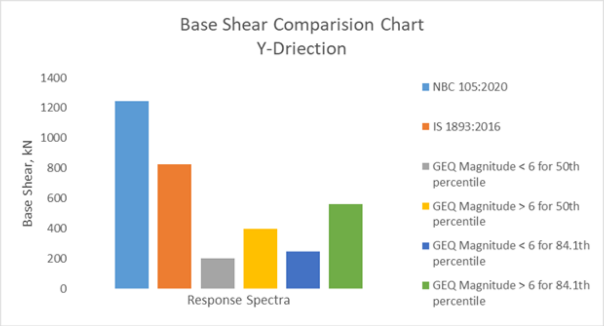


Figure 7: Inter story drift in Y-direction from RSM)

code based spectra.

4. Conclusion

This present study developed site specific response spectra for rock sites in the Kathmandu Valley by using recorded ground motion from the 2015 Gorkha Earthquake motions. The analysis of a typical RC building using these spectra, in comparison with code based approaches, provides a number of key conclusions that have important practical implications:

1. Design spectra from NBC 105:2020 have larger spectral acceleration at most periods than IS 1893:2016 as well as from the Gorkha Earthquake records for the entire range of magnitudes, especially for smaller magnitude events, Mw < 6. However, the GEQ based spectra surpass the code spectra for larger magnitudes of Mw > 6 in the period range dominated by displacement ($T > 2.0s$). This suggests that while codes are safe for short period structures, they may underestimate the demand on taller, more flexible buildings during a major seismic event like the Gorkha main shock.
2. The practical implication of the developed spectra has a significant reduction in calculated seismic demand. The base shear from the GEQ spectra was 40-85% less than the code based values. Similarly, inter-story drift and story displacement were found to be several times smaller. This suggests that structures designed strictly to the code spectra for rock sites may have a significantly higher safety margin against the collapse for ground motions similar to the Gorkha sequence.
3. The result suggest region specific and event conditioned response spectra should be included in seismic design practice in Nepal.

This study focused on rock site conditions. Future work should expand this methodology to include the deep soil sites prevalent in Kathmandu Valley, that is known to amplify the ground motions. Furthermore, the development of a larger database of response spectra from various Nepalese earthquake enables the derivation of more robust and representative regional design spectra, ultimately contributing to ongoing evolution and refinement of the Nepal Building Code.

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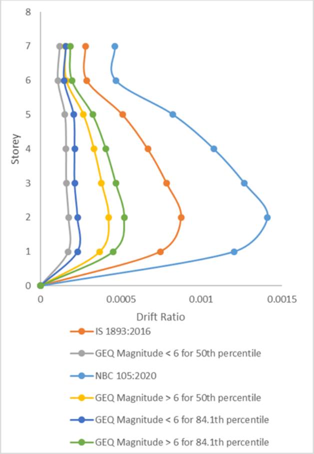

Figure 8: Inter story drift in X-direction from RSM

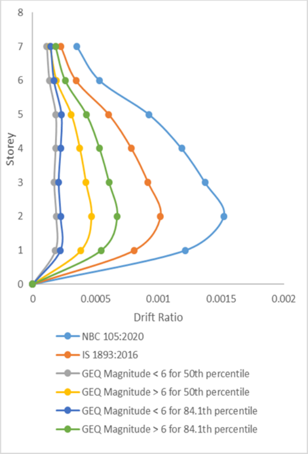

Figure 9: Inter story drift in X-direction from RSM

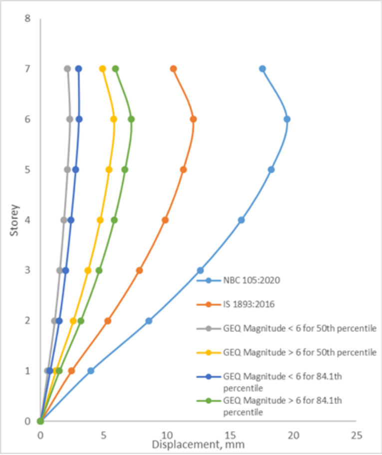

Figure 10: Displacement in X-direction from RSM

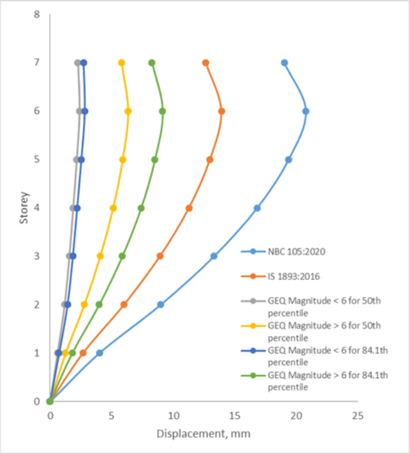

Figure 11: Displacement in Y-direction from RSM

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