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The effect of different earthquake ground motion level on performance of reinforced-concrete structures

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ABSTRACT

Four different earthquake ground motion levels with different probabilities of exceedance were expressed with the current seismic design code. In this study, earthquake-structural parameters were obtained by taking into account four different ground motion levels for four different provinces with different earthquake hazards. Structural analyses were carried out using different earthquake ground motion levels obtained for each province. In the structural analysis, a sample reinforced-concrete structure with the same structural characteristics was selected. The results were obtained by using both ground motion levels and design spectra for four provinces. With this study, both the earthquake hazard and the ground motion level change were examined separately. It was determined that the two variables significantly changed the target displacement values expected from the structure.

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1. Introduction

Renewal and improvement is inevitable in earthquake resistant building design rules over time. In addition, since the building and construction technologies have developed, the rules related to these should also be added to the seismic design codes. In this context, this process continued in Turkey with the studies carried out over time. Earthquake resistant building design rules, which started in the 1940s, were renewed on different dates and used within the scope of structural design, analysis and evaluation. The seismic design code, which has been used since 2007, was finalized in 2018 with the necessary updates and additions. One of the important additions was made at earthquake ground motion levels. In the previous code, only earthquake ground motion level, which had a recurrence period of 475 years and was expressed as a standard design earthquake, was used. However, with the current code, four different earthquake ground motion levels with different recurrence periods and exceedance probabilities have been specified. The earthquake parameter and design spectra differ for each ground motion level.

The usage of site-specific design spectra is also one of the important updates with current code. Seismicity parameters and design spectra are obtained specifically for any location and show differences with this update. The design spectra can be obtained by using the local soil conditions and seismicity parameters of any location together (Işık et al., 2020; Karaşin et al., 2020). The differentiation of the design spectra significantly effects the expected target displacements from the buildings. Damage estimation and realistic performance of buildings depend on the correct determination of design spectra (Kutanis et al., 2018; Işık et al., 2016).

There are many studies examining the changes between the last two regulations. In these studies, earthquake force calculation methods, base shear forces, displacements, period, target displacements, spectrum curves and section damage values were examined and compared (Işık et al., 2021; Aksoylu et al., 2020; Aksoylu and Arslan, 2021; Keskin and Bozdoğan, 2018; Koçer et al., 2018; Bozer, 2020; Ulutaş, 2019; Adar et al., 2021; Seyrek, 2020; Büyüksaraç et al., 2021; Başaran, 2018; Nemutlu and Sarı, 2018; Işık et al., 2021a; Yalın and Ulutaş, 2021; Peker ve Işık, 2021; Akyıldız et al., 2021). In the study conducted by Başaran and Hiçyilmaz (2020), the effects of

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different earthquake ground motion levels on reinforced-concrete frames were examined. The results obtained by considering different local ground conditions and four different ground motion levels for Afyon province were compared.

Within the scope of this study, four different provinces located in different earthquake zones were selected and earthquake-structure parameters were obtained for four different earthquake ground motion levels for each province. Design spectra were obtained by considering different ground motion levels for each province. Structural analyses were carried out using these obtained design spectra. Base shear forces, elastic and effective stiffness values and target displacement values expected from the structure were obtained for four different ground motion levels, separately. Two different variables were selected in this study such four different provinces located in different earthquake zones and four different ground motion levels. In this study, the interaction of these two variables was tried to be examined.

2. Comparison of Earthquake Parameters

While selecting different provinces within the scope of this study, four different provinces located in different earthquake zones were selected in the previous earthquake zone map. As Erzincan 1st degree earthquake zone; Adana is a 2nd degree earthquake zone; Gümüşhane was chosen as the 3rd degree earthquake zone and Ankara as the 4th degree earthquake zone. The representation of these selected provinces on the current earthquake hazard map is given in Figure 1.

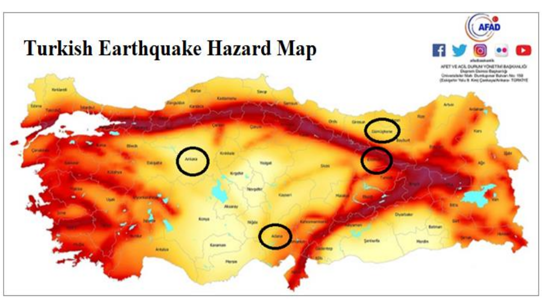

Figure 1. Turkish Earthquake Hazard Map and the studied locations

In TSDC-2007, while only the standard design earthquake ground motion with a recurrence period of 475 years and a probability of exceedance of 10% in 50 years was taken into account, three more ground motion levels with a probabilities of exceedance in 50 years were added in the current code. Four different earthquake ground motion levels in the current code are given in Table 1.

Table 1. Earthquake ground motion levels (TEBC-2018)

Earthquake Level	Recurrence Period	Probability of Exceedance	Description
DD-1	2475	2%	Largest arthquake
DD-2	475	10%	Standard earthquake
DD-3	72	50%	Frequent earthquake
DD-4	43	68%	Service earthquake

Earthquake parameters for any geographic location can be obtained very easily and practically with the help of Turkey Earthquake Hazard Maps Interactive Web Application. The application gives earthquake parameters and design spectra, taking into account the earthquake ground motion level and local soil classes, in accordance with the current code. In this study, the ZC local soil type in TBEC-2018 was taken into account in order to reveal the changes in the structural analysis results. The peak ground acceleration (PGA), the peak ground velocity (PGV), map spectral acceleration coefficients (S_S and S_1), local ground effect coefficients (F_S and F_1) for four different provinces were obtained for different ground motion levels. The design spectral acceleration coefficients (S_{DS} and S_{D1}) were obtained separately. Horizontal and vertical elastic design spectra were obtained with the help of the application. The comparison of PGA and PGV values for different earthquake ground motion levels is shown in Table 2.

Table 2. The comparison of PGA and PGV for selected provinces

Province	PGA (g) Probability of exceedance in 50 years				PGV(cm/s) Probability of exceedance in 50 years			
	2%	10%	50%	68%	2%	10%	50%	68%
Erzincan	1.09	0.60	0.22	0.15	74.61	39.34	12.4	8.38
Adana	0.45	0.23	0.08	0.06	24.16	11.33	4.56	3.29
Gümüşhane	0.35	0.18	0.07	0.05	21.95	11.89	5.26	3.71
Ankara	0.30	0.15	0.06	0.04	17.93	10.17	4.33	3.16

The comparison of the short period map spectral acceleration coefficient (S_S) and the map spectral acceleration coefficient (S_1) for the 1.0 second period for different probabilities of exceedance in 50 years are shown in Table 3.

Table 3. Comparison of map spectral acceleration coefficients

Province	S_S Probability of exceedance in 50 years				S_1 Probability of exceedance in 50 years			
	2%	10%	50%	68%	2%	10%	50%	68%
Erzincan	2.71	1.44	0.50	0.33	0.84	0.41	0.13	0.09
Adana	1.07	0.53	0.19	0.13	0.26	0.13	0.05	0.04
Gümüşhane	0.85	0.43	0.16	0.11	0.26	0.13	0.06	0.04
Ankara	0.70	0.35	0.13	0.09	0.21	0.12	0.05	0.04

The comparison of spectral acceleration coefficients was made only for DD-2 ground motion level. The reason for this is that in the previous earthquake code, only the ground motion level with a recurrence period of 475 years and a probability of exceedance 10% in 50 years was used. The comparison of the spectral acceleration coefficients according to the last two seismic design codes is shown in Table 4. No comparisons were made in the vertical direction since there were no vertical values in the previous code.

Table 4. Comparison of spectral acceleration coefficients

DD-2	Spectral Acceleration Coefficient				Corner Periods			
	All soil types		ZC		ZC		ZC	
PROVINCE	TSDC-2007		TBEC-2018		TSDC-2007		TBEC-2018	
	S_{DS}	$0.40S_{DS}$	S_{DS}	$0.40S_{DS}$	T_A	T_B	T_A	T_B
Erzincan	1	0.40	1.726	0.690	0.15	0.60	0.072	0.360
Adana	0.75	0.30	0.682	0.273	0.15	0.60	0.058	0.288
Gümüşhane	0.50	0.20	0.554	0.223	0.15	0.60	0.081	0.404
Ankara	0.25	0.10	0.448	0.179	0.15	0.60	0.080	0.401

With the updated code, local ground effect coefficients (F_s and F_1) were used for the first time. The short period map spectral acceleration coefficient for the period of 0.2 s (S_S) and map spectral acceleration coefficient for the period of 1.0 s (S_1) was also obtained for all locations. Horizontal elastic design acceleration spectrum corner period (T_A and T_B) and vertical elastic design acceleration spectrum corner period (T_{AD}, and T_{BD}) were obtained from the application. The results obtained for the same ground motion levels for four different provinces with different seismicity characteristics and considered within the scope of the study were also compared. The comparison of the earthquake parameters obtained for DD-1, which is called the largest earthquake, is shown in Table 5.

Table 5. The comparison of earthquake parameters for DD-1

Province	F_S	F_1	S_{DS}	S_{D1}	T_A	T_B	T_{AD}	T_{BD}
Erzincan	1.200	1.400	3.256	1.169	0.072	0.359	0.024	0.120
Adana	1.200	1.500	1.283	0.387	0.060	0.302	0.020	0.101
Gümüşhane	1.200	1.500	1.015	0.393	0.077	0.387	0.026	0.129
Ankara	1.221	1.500	0.851	0.318	0.075	0.374	0.025	0.125

The comparison of the earthquake parameters obtained for DD-2, which is called the standard design earthquake, is shown in Table 6.

Table 6. The comparison of earthquake parameters for DD-2

Province	F_S	F_1	S_{DS}	S_{D1}	T_A	T_B	T_{AD}	T_{BD}
Erzincan	1.200	1.500	1.726	0.621	0.072	0.360	0.024	0.120
Adana	1.288	1.500	0.682	0.197	0.058	0.288	0.019	0.096
Gümüşhane	1.300	1.500	0.554	0.224	0.081	0.404	0.027	0.135
Ankara	1.300	1.500	0.448	0.180	0.081	0.404	0.027	0.135

The comparison of the earthquake parameters obtained for DD-3, which is called the frequent earthquake, is shown in Table 7. DD-4, which is called the service earthquake, is shown in Table 8.

Table 7. The comparison of earthquake parameters for DD-3

Province	F_S	F_1	S_{DS}	S_{D1}	T_A	T_B	T_{AD}	T_{BD}
Erzincan	1.300	1.500	0.650	0.199	0.061	0.307	0.020	0.102
Adana	1.300	1.500	0.246	0.076	0.062	0.311	0.021	0.104
Gümüşhane	1.300	1.500	0.204	0.091	0.090	0.448	0.030	0.149
Ankara	1.300	1.500	0.169	0.076	0.091	0.453	0.030	0.151

Table 8. The comparison of earthquake parameters for DD-4

Province	F_S	F_1	S_{DS}	S_{D1}	T_A	T_B	T_{AD}	T_{BD}
Erzincan	1.300	1.500	0.434	0.129	0.059	0.297	0.020	0.099
Adana	1.300	1.500	0.168	0.054	0.064	0.322	0.021	0.107
Gümüşhane	1.300	1.500	0.140	0.065	0.092	0.459	0.031	0.153
Ankara	1.300	1.500	0.122	0.056	0.091	0.454	0.030	0.151

Comparison of horizontal and vertical elastic design spectra obtained for different earthquake ground motion levels for the provinces considered in the study was also made. Comparison of the design spectra obtained for different ground motion levels for the province of Erzincan is shown in Figure 2.

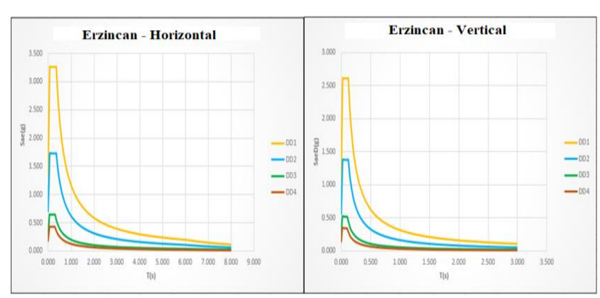

Figure 2. Comparison of the design spectra obtained for different ground motion levels for Erzincan province

The comparison of the horizontal and vertical elastic design spectra obtained for the DD-2 ground motion level, which is the standard design earthquake, for four different provinces is shown in Figure 3.

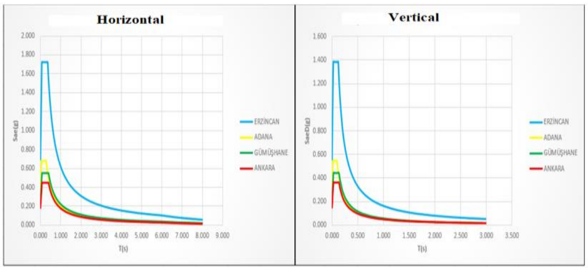

Figure 3. Comparison of the design spectra obtained for different ground motion levels for all provinces

The earthquake parameters obtained for different earthquake ground motion levels have taken different values for provinces with different seismicity conditions for same local soil type. In addition, earthquake parameters changed as the probability of exceedance in 50 years changed for each province. Among the provinces considered within the scope of the study, the map PGA, PGV and map spectral acceleration coefficients (S_S and S_1) had the highest values in Erzincan. The lowest values were obtained for Ankara. The local soil coefficients F_S and F_1 values were equal to each other except for very slight differences, since the local soil type did not change. The variation of the local soil coefficients (F_s and F_1) directly affects the S_{DS} and S_{D1} parameters. The short period design spectral acceleration coefficient (S_{DS}) has the highest value in Erzincan and the lowest value in Ankara.

3. Comparison of Structural Analyses Parameters

Pushover analysis is the one of the commonly used approaches to determine the seismic capacities of buildings in the design and evaluation of structures (Estêvão and Oliveira, 2015; Ademoviç et al., 2013; Karakaš et al., 2018; Bilgin and Frangu, 2017). This type of analysis was also used in this study. Typical pushover curve and all displacements calculated for structural analysis are shown in Figure 4.

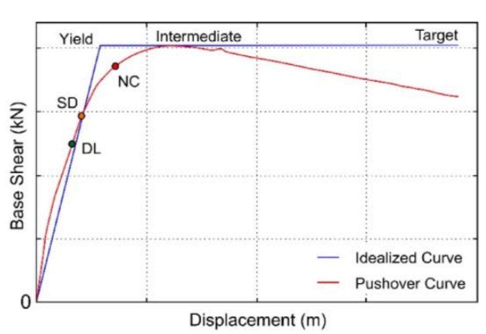

Figure 4. Typical pushover and idealized curves and calculated displacements

In performance-based earthquake engineering, it is important to determine target displacements for damage estimation when certain performance limits of structural elements are reached. In the structural analysis, limit states given in Eurocode-8 (Chapter 3) (Eurocode, 2005; Pinto and Franchin, 2011) for worldwide used damage estimation were taken into account. Accordingly, the proposed limit states are shown in Table 9.

Table 9. Limit states in Eurocode 8 (Part3)

Limit State	Description
Damage Limitation (DL)	Only lightly damaged, damage to non-structural components economically repairable
Significant Damage (SD)	Significantly damaged, some residual strength and stiffness, non-structural components damaged, uneconomic to repair
Near Collapse (NC)	Heavily damaged, very low residual strength and stiffness, large permanent drift but still standing

A 6-storey reinforced-concrete building was chosen as an example. Since the structure was chosen as symmetrical, structural analyses were carried out only in the X direction with Seismostruct software (Seismosoft, 2018). There is no irregularity in the selected reference building. In the RC sample building model, C25-S420 was chosen as the material. ϕ10/10 is chosen as transverse reinforcement for both columns and beams. The longitudinal reinforcement for the columns is 4ϕ20 at the corners and 8ϕ16 for the other longitudinal reinforcements. For the beams, 4ϕ14 was chosen in the lower and upper regions and 2ϕ12 was chosen as the body reinforcement. The blueprint of the considered reinforced-concrete structure is given in Figure 5.

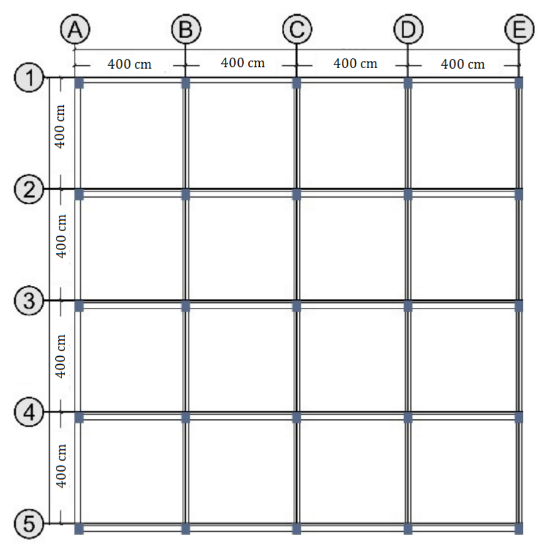

Figure 5. The blueprint of sample RC building

The 3D finite element model of the sample RC building is given in Figure 6.

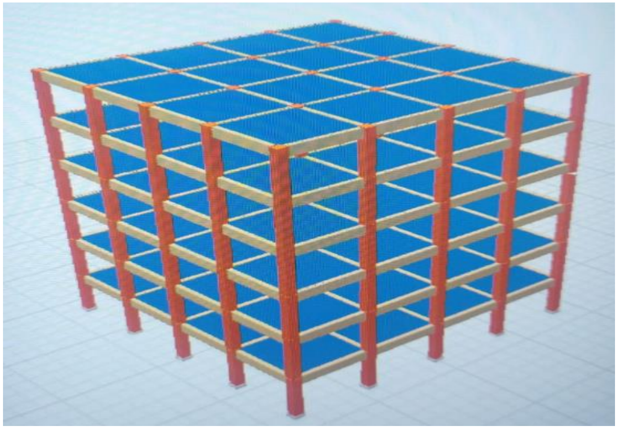

Figure 6. The 3D model of the sample building

The sample RC building was analysed in all provinces without changing its structural properties. The natural vibration period for the sample RC building was obtained as 0.351 s for all provinces and all ground motion levels.

Comparison of structural results obtained for DD-1 ground motion level was shown in Table 10; comparisons for DD-2 ground motion level was in Table 11; the comparison of the results for the DD-3 ground motion level was shown in Table 12 and the comparison of the results obtained when the DD-4 ground motion level was shown in Table 13. The elastic stiffness value (K_elas) and effective stiffness (K_eff) values for each structural model were obtained directly using the stiffness reduction coefficients predicted in the algorithm.

Table 10. Comparison of results for DD-1 ground motion level

Province	Base Shear (kN)	K_elas	K-eff	DL	SD	NC
Erzincan	6434.74	174945.59	82880.23	0.137	0.179	0.318
Adana	6434.74	174945.59	82880.23	0.053	0.068	0.124
Gümüşhane	6434.74	174945.59	82880.23	0.042	0.054	0.095
Ankara	6434.74	174945.59	82880.23	0.035	0.045	0.078

Table 11. Comparison of results for DD-2 ground motion level

Province	Base Shear (kN)	K_elas	K-eff	DL	SD	NC
Erzincan	6434.74	174945.59	82880.23	0.071	0.093	0.169
Adana	6434.74	174945.59	82880.23	0.027	0.035	0.061
Gümüşhane	6434.74	174945.59	82880.23	0.022	0.028	0.048
Ankara	6434.74	174945.59	82880.23	0.018	0.023	0.039

Table 12. Comparison of results for DD-3 ground motion level

Province	Base Shear (kN)	K_elas	K-eff	DL	SD	NC
Erzincan	6434.74	174945.59	82880.23	0.026	0.033	0.057
Adana	6434.74	174945.59	82880.23	0.010	0.0128	0.022
Gümüşhane	6434.74	174945.59	82880.23	0.008	0.011	0.018
Ankara	6434.74	174945.59	82880.23	0.007	0.009	0.015

Table 13. Comparison of results for DD-4 ground motion level

Province	Base Shear (kN)	K_elas	K-eff	DL	SD	NC
Erzincan	6434.74	174945.59	82880.23	0.018	0.0230	0.039
Adana	6434.74	174945.59	82880.23	0.0068	0.0087	0.015
Gümüşhane	6434.74	174945.59	82880.23	0.006	0.0073	0.013
Ankara	6434.74	174945.59	82880.23	0.005	0.006	0.011

There was no change in the natural vibration period for the sample RC building with the same structural properties, since the structural properties did not change. This situation remained valid for the base shear force, elastic and effective stiffness values of the structure and no change was obtained. The target displacement values expected from the structure at different earthquake ground motion levels for each province have changed significantly. As the probability of exceedance for the province decreases, that is, in case of larger earthquakes, the displacement demands have taken on higher values. These values decreased in smaller earthquakes that were more frequent. When the values obtained for different provinces are compared, in case the PGA values increase, the displacement values to be used in the performance evaluation of the buildings also increased significantly. DD-2 earthquake ground motion with a recurrence period of 475 years and a probability of exceedance of 10% in 50 years, which is the standard design earthquake level, is taken into account as an example for the comparisons between the maximum ground acceleration (PGA) obtained and the target displacements. The comparison of PGA values and target displacement values obtained for this ground motion level is shown in Table 14.

Table 14. Comparison of PGA and target displacement values

Province	PGA (g)	DL	SD	NC
Erzincan	0.598	0.071	0.093	0.169
Adana	0.232	0.027	0.035	0.061
Gümüşhane	0.182	0.022	0.028	0.048
Ankara	0.149	0.018	0.023	0.039

4. Conclusions

Earthquake ground motion levels are expressed with different probabilities of exceedance with the current seismic design code. The number of one ground motion level in the previous code was increased to four. Within the scope of this study, four different ground motion levels specified in the current seismic design code were chosen as the first variable. In addition, with the current code, earthquake parameter and site-specific design spectra for studied geographical location are obtained. Four different geographical locations were chosen as the second variable. Erzincan for the 1st degree earthquake zone; Adana for the 2nd degree earthquake zone; Gümüşhane for the 3rd degree earthquake zone and Ankara for the 4th degree earthquake zone was taken into consideration. Firstly, earthquake parameters were obtained for both ground motion levels and provinces. Structural analyses were carried out for a sample RC building using the obtained design spectra.

Since the structural properties did not change, there was no change in the base shear forces, elastic and effective stiffness values obtained. However, as the design spectrum values changed, the target displacement values used for damage estimation in structures changed significantly. This has once again revealed that the performance levels and damage estimates for the structures will be more realistic. In this context, it shows that the usage of site-specific design spectra with the current code is an important gain.

Percentages of change between TSDC-2007 and TBEC-2018 in the design spectral acceleration coefficient (S_{DS}) for ZC local soil for the short period; 72.6% in Erzincan, 9.07% in Adana, 10.8% in Gümüşhane and 79.2% in Ankara. Design spectral acceleration coefficient (S_{D1}) for 1.0 second period, percentages of change between TSDC-2007 and TBEC-2018 for ZC local ground; Erzincan province has 72.5%, Adana province 9.0%, Gümüşhane province 11.5% and Ankara province 79.0%. The percentages of change for the design spectral acceleration coefficient for the short period of the values obtained from DD-1, which is called the largest earthquake, to DD-4, which is the service earthquake ground motion level; There is a decrease of 86.67% in the province of Erzincan, 86.91% in the province of Adana, 86.21% in the province of Gümüşhane and 85.66% in the province of Ankara.

For the peak ground acceleration (PGA) value, as the probability of exceedance in 50 years increases by 2%, 10%, 50%, 68%; there is a decrease of 86.49% in Erzincan, 87.33% in Adana, 86.44% in Gümüşhane and 85.81% in Ankara. For the peak ground velocity (PGV) value, as the probability of exceedance in 50 years increases by 2%, 10%, 50%, 68%; there is a decrease of 88.76% in Erzincan, 86.40% in Adana, 83.09% in Gümüşhane and 82.36% in Ankara.

If the same local soil condition is taken into account, the short period map acceleration coefficient (S_S) increases as the probability of exceedance in 50 years increases according to 2%, 10%, 50%, 68% at different earthquake ground motion levels; there is a decrease of 87.67% in Erzincan, 87.93% in Adana, 87.23% in Gümüşhane and 86.51% in Ankara. The map spectral acceleration coefficient (S_1) for the 1.0 second period increases as the probability of exceedance in 50 years increases according to 2%, 10%, 50%, 68% at different earthquake ground motion levels; there is a decrease of 89.70% in Erzincan, 86.05% in Adana, 83.59% in Gümüşhane and 82.55% in Ankara.

Percentage of change in target displacement values from DD-1 to DD-4 for different earthquake ground motion levels for each province; Erzincan province DL 86.86%, SD 87.15%, NC 87.84%; Adana province DL 87.17%, SD 87.21%, NC 87.90%; Gümüşhane province DL 85.71%, SD 86.48%, NC 86.73% and Ankara province DL 85.71%, SD 86.67%, NC 85.90%.

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