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Article

Simplified Seismic Out-of-Plane Demand and Capacity Assessment for Mortar-Jointed Bricks Masonry Infills in Seismic Regions of Pakistan

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Abstract

In this paper, a practical, district-scale framework to estimate the seismic out of plane (OOP) demand of mortar-jointed brick infills in Pakistan is developed and the demand versus experimental validated capacity is compared. The expression of ASCE 7-16/7-22 OOP is reduced algebraically to an expression with only one coefficient of the district, $\alpha_{district}$, such that OOP force is computed by simply multiplying $\alpha_{district}$ and W_P. Based on the S_{DS} maps of Pakistan in classes A-E, the calculation of $\alpha_{district}$ is presented in this paper to all administrative districts of Pakistan except those soil classes that need site-specific analysis according to BCP 2021. When parametric analysis is performed, the ASCE height amplification term converges after 8 storeys (f ≈1.4 - 1.5 for I_p =1.0; f ≈1.7 - 1.8 for I_p =1.5), justifying an envelope constant for national level rapid screening of infill walls enclosed by RC frame, and it is reasonable to take the constant f-factor for all infills especially for infills after 7th storey. Quasi-static experiment of representative Pakistani infills made of mortar-jointed bricks infill under out-of-plane (OOP) loading were carried out. It was concluded that the Ricci et al. capacity model compared (capacity ratios 0.98) and was used to map capacity against the OOP demand for each district of Pakistan. Comparisons between demands and capacities indicate that in most districts 4.5-in panels, while 9-in panels are not safe in high-seismic regions and on weak soils for essential facilities (Ip=1.5). The $\alpha_{district}$ dataset allows high speed screening (Rapid Screening), district-scale vulnerability mapping, and similar insertion of OOP checks into code amendments and standard design practice by practitioners.

Keywords: Seismic assessment; Masonry infills; Out-of-plane demand; ASCE 7-16; Pakistan building code; Rapid screening.

1. Introduction

Masonry is among the oldest and most common form of construction material in the world because it is relatively cheap, accessible and it serves its purpose [1]. Over 58 percent of the buildings in Pakistan is made up of mortar-jointed masonry units, which is

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mainly clay brick masonry (Bureau of Statistics of Pakistan, 2021). Masonry infills in the case of reinforced concrete (RC) frame structures is also the most widespread type in the country, are used as enclosure, partition and facade elements and are conventionally categorized as non-structural elements (NSEs) [2]. Regardless of the classification, infill walls experience high seismic forces, such as in-plane (IP) and out-of-plane (OOP) forces, and their collapse has been identified many times to cause losses in terms of economic values, life safety and post-earthquake building downtime [[3], [4]]. Major recent earthquakes, including L'Aquila (2009) [5], Lorca (2011) [6], and Emilia (2012) [4], have shown that the OOP collapse of the masonry infills is also one of the most common and dangerous types of non-structural damage [[7], [8]].

In the last few decades, experimental, analytical and empirical studies have been conducted to determine the OOP behavior of masonry infills. It has been experimentally studied to quantify failure mechanisms, arching action, effects of slenderness and frame-infill interaction through laboratory and full-size experiments using inertial airbag loading, point and four-point bending, sequential IP-OOP testing, shake-table excitations [[9], [10], [11], [12], [13], [14]]. On the basis of this literature, there has been a number of analytical and empirical formulations of OOP capacity of masonry infill panel, including those by [15], [9], [10], [11], [16], [17], and [18].

Although the infill capacity was a long-established study, the ASCE 7-16/7-22 [19] height-dependent inertial amplification expression dominates OOP seismic demand in modern-day engineering practice, taking into consideration the design spectral acceleration (S_{DS}), importance factor (I_P), response modification factor (R_P) and relative height in the structure (z/h). Though it is physically intensive, this formulation cannot be easily used to screen quickly, assess regional vulnerability, or implement a code level quick assessment since it needs building-specific parameters and cannot be directly implemented at the scale of cities, districts, or national inventories.

Although the literature of masonry infill behavior is extensive in the world, Pakistan has no district-resolved OOP seismic demand database of masonry panels, simplified force coefficient that can be directly used in the form (F_{OOP} = (coefficient) x W), and an OOP capacity model calibrated to use locally available mortar-jointed brick masonry. In addition to this, seismic code (BCP-2021) [20] in Pakistan offers short period and one second spectral acceleration (S_S and S_1) and has no specifications on the OOP demand and capacity of masonry fillings. Consequently, the safety of OOP is not systematically considered during design, and the practice of regulations is not applied even in moderate to high seismic areas.

This is a severe deficiency since masonry infills in Pakistan vary vastly with international studies that are focusing on infills units that are having completely different strength, craftsmanship, and geometry of construction. Local-manufactured clay bricks and mortars have various stiffness, cracking behavior and failure mode than hollow clay blocks and engineered masonry units that are actively researched in Europe and North America. As a result, it is subject to a high degree of uncertainty regarding the direct transfer of the international OOP capacity models to the Pakistani construction practice before properly investigating the local construction of the infills.

Throughout the course of experimental studies, it was established that OOP response depends on a combination of interacting parameters, such as, slenderness ratio, aspect ratio, stiffness of the boundary, interface continuity, and previous in-plane damage. Since the slenderness increases, capabilities decrease sharply [[10], [21]] and aspect ratio has a significant effect on redistribution of loads and failure modes [22]. Frame stiffness and frame boundary restraint are crucial to the development of arching action [[9], [10]], and inter-frame and inter-interface discontinuities can also decrease OOP capacity by a factor of 80% [[23], [24], [25]]. Moreover, previous damage in the in-plane direction might reduce OOP resistance by two to four times [[11], [26], [27]]. With this vast amount of additional worldwide evidence, there is practically no experimental information on the Pakistani masonry infills, which is why their actual OOP seismic strength largely remains unknown.

OOP capacity estimation are discussed in the international standards like Eurocode 6 [28], FEMA 306 [29] and ASCE 41-17 [30] that give procedures to estimate the capacity, but OOP seismic demand is only defined in ASCE 7-16/7-22 [19] by an expression of height-dependent dynamic amplification that is not formulated to be applied on national scale in common design practices because of the lack of simplification of the formula in ASCE 7-16 [19] and emphasis on the OOP assessment for the NSE infill walls enclosed by RC frames.

Based on this, this research work aims to develop a simplified and nationally applicable methodology to assess the seismic out of plane safety of mortar-jointed masonry infills in Pakistan by (i) deriving simplified district specific OOP seismic demand factors for each soil class of each district of Pakistan (α_{district}) under ASCE 7-16/7-22 on using national hazard and site-class data (S_S and S_1) of BCP-2021 [20], and (ii) comparing the demands to a validated OOP capacity model based on local experimental testing. The recommended framework offers a logical ground on which future modifications of BCP-2021 can be made and a practical tool to be used by practicing engineers to assess the infill seismic safety in a short period of time.

2. Capacity Validation and Formula Simplification.

This paper constructs a simplified framework of assessing the out of plane (OOP) seismic resistance of masonry infills in Pakistan by combining (i) a simplified ASCE 7-16/7-22 OOP demand model, (ii) experimentally validated OOP capacity correlations, and (iii) a district-wide seismic hazard dataset of soil type A - E. The methodology starts with the complete ASCE 7-16/7-22 OOP acceleration equation and converts it to a constant-multiply form whereby the OOP demand may be determined directly as a factor multiplied by the weight of infill wall. This is a simplification that allows quick screening and comparison of the OOP demand and capacity in Pakistan. Once the demand model is in place, one then uses the experimental strength of mortar-jointed brick infills under four-point loading in order to prove the most appropriate analytical capacity equation.

2.1 Simplifying the ASCE 7-16 Out-of-Plane Force Equation

The ASCE 7-16 prescribes the following expression for the horizontal OOP seismic force acting on nonstructural elements or masonry walls:

$$F_p = 0.4a_p S_{DS}\, W_p \frac{I_p}{R_p}\left(1+2\frac{z}{h}\right)$$

subject to the bounds:

$$F_{p,\min} = 0.3S_{DS}W_p\frac{I_p}{R_p}, F_{p,\max} = 1.6S_{DS}W_p\frac{I_p}{R_p}$$

For conventional masonry infills in RC frames, the parameters are typically taken as:

$$a_p = 1.0, R_p = 1.0, I_p = 1.0 \text{ or } 1.5.$$

$$F_{p,min} = (0.3\ for\ Ip = 1\ or\ 0.45\ for\ Ip = 1.5)S_{DS}W_p,$$

$$F_{p,\max} = (1.6\ for\ Ip = 1\ or\ 2.4\ for\ Ip = 1.5)S_{DS}W_p.$$

The building height term (z/h) in the general form makes the OOP demand to be story-to-story variant. Even then, according to surveys of Pakistan, the overwhelming majority of infills are associated with low- and mid-rise buildings in which the height-ratio term does not introduce significant disparity. Moreover, story-specific acceleration amplification is rarely used in the existing design practice in Pakistan. In order to allow the national scale comparison of infill types, the term is eliminated by introducing the envelope condition of the whole height range. Doing away with z/h, and rearranging the equation, the OOP force is:

$$F_p = \alpha\, S_{DS}\, W_p$$

The upper and lower ASCE bounds are next addressed. Instead of switching between three expressions (general, minimum, and maximum), a unified constant factor is used:

$$F_{OOP} = \alpha_{\text{district}}\, W_p$$

where $\alpha_{\text{district}} = f(S_{DS})$ incorporates the actual S_{DS} value of the district and satisfies:

$$0.3S_{DS} \le \alpha_{\text{district}} \le 1.6S_{DS}$$

By computing α_{district} directly from the simplified formula and comparing with the limits, a single district-specific value is produced for all soil classes (A-E), for both importance factors $I_p = 1.0$ and $I_p = 1.5$. This allows the OOP demand in any district of Pakistan to be obtained by a single multiplication with the infill weight W_p, greatly simplifying engineering application.

Thus, the ASCE 7-16/7-22 equation is rigorously reduced to a factor-based demand expression of the form:

$$F_{OOP} = \underbrace{(\alpha_{\text{district}})}_{\text{ASCE-derived Factor}} \times W_p.$$

2.2 Extraction of Factor for All Districts of Pakistan

Using the complete S_{DS} database for Pakistan (for Soil Classes A, B, C, D, and E), the derived expression for α_{district} was applied to compute OOP demand coefficients for all administrative districts. Districts with S_{DS} values that exceeded ASCE 7-16/7-22 bounds were flagged as requiring site-specific seismic hazard analysis. The resulting tables of α-factors enable direct computation of OOP demand without iterative formula evaluation or height-location modeling, marking the first such dataset for Pakistan.

2.3 Experimental Determination of Out-of-Plane Capacity Using Four-Point Loading

To obtain a realistic and representative OOP capacity benchmark for Pakistani brick infills, a full-scale RC frame was constructed and infilled with conventional mortar-jointed brick masonry. The frame geometry was selected to reflect typical Pakistani school buildings, while ensuring compatibility with laboratory handling constraints. Columns measuring 12 in × 12 in and beams measuring 12 in × 10 in were reinforced according to standard practice. The infill was constructed before the beam closure to guarantee full engagement at all interfaces. Steel dowels were installed at column-infill joints as required by TMS 402/602-16 to ensure OOP stability without introducing in-plane restraint.

A four-point loading rig was fabricated using W-section secondary beams and a C-section primary beam mounted to a 50-ton load cell on the strong wall of the Earthquake Engineering Center (EEC), UET Peshawar. The loading points were arranged to apply uniform bending across the central third of the infill height and span, closely replicating common laboratory OOP testing protocols. Eleven displacement transducers were strategically placed to measure mid-span deflection, sliding at the interfaces, and deformation symmetry. A semi-cyclic, displacement-controlled loading scheme was adopted, gradually increasing peak displacement from 2.5 mm to 70 mm.

The peak OOP force was extracted from the envelope curve, providing the experimental OOP capacity F_{exp}. Because four-point loading produces a bending-dominated failure, whereas most analytical models are formulated for pressure-type (airbag) loading, the Trapani conversion factor (α-method) was applied to convert the measured force to an equivalent airbag-type capacity, allowing fair comparison with analytical predictions.

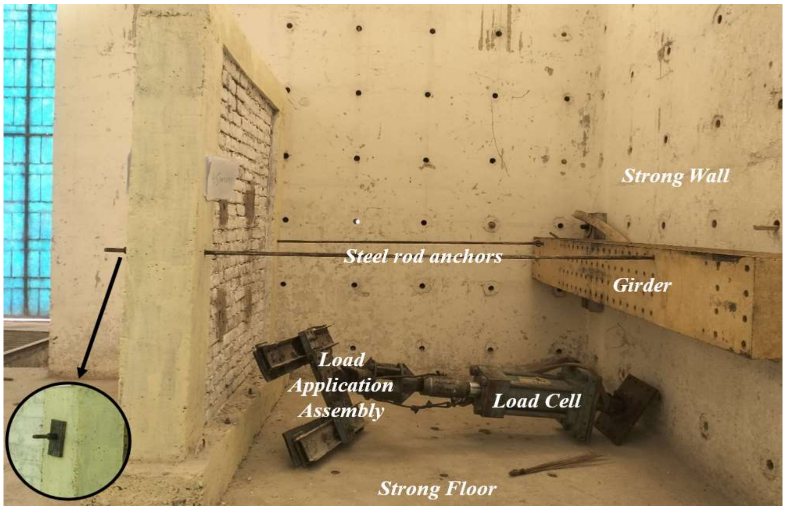

Figure 1. Four-Point Loading test for OOP Capacity Assessment

2.4 *Validation and Selection of the Analytical Capacity Model*

Some popular analytical OOP capacity models were compared with the experimental data, such as McDowell, Dawe and Seah, Angel, Flanagan and Bennett, Klingner, Moghaddam, Trapani and Ricci. There was a wide margin of over- or under-prediction of the tested capacity, whereas the empirical model proposed by Ricci et al. (2018) demonstrated great agreement with the ratio between the capacity being 0.94-0.98. Due to its reliance on three physically significant quantities (mortar strength, thickness and slenderness), and its good performance against true Pakistani masonry, the equation of Ricci became the approved and functional national equation of OOP capacity estimation.

After validation, the Ricci equation was used to determine OOP capacities of all infill thickness of 9 in, heights (8ft) and lengths (8 ft) that were used in this research. This ability is then equated to the simplified factors of ASCE-based OOP demand factors to calculate the Factor of Safety (FOS) of each district and class of soil in Pakistan.

Table 1. Comparison of Analytical Capacity with Experimental Capacity

Description	**Bricks infill**	
	Load (tons)	$P_{analytical}/P_{exp}$
Experimental P_{OOP}	16.35	1
Flanagan & Bennett, 1999	22.66	1.36
Angel 1996	13.61	0.83
Dawe & Seah, 1989	22.66	1.36
Klingner et al., 1996	48.46	2.96
H. Moghaddam & N. Goudarzi, 2010	14.34	0.87
Fabio Trapani et al., 2021	15.01	0.91
Ricci et al., 2018	12.13	0.94

3. Results and Discussion

3.1 Effect of storey's heights over $\alpha_{\text{district}} = \text{f x S}_{\text{DS}}$

The dependence of the f-factor simplified from the ASCE 7-16 formula on the height of the building is initially tested to determine the need to maintain the height-response to the expression in the large-scale application. Figure 2 and Figure 3 respectively shows the analysis of the factor ($f=0.4(1+2(z/h))$) of ordinary buildings of Ip =1 and $f = 0.6\ (1+2\ (z/h))$ of essential buildings of Ip = 1.5 as a function of the number of storeys.

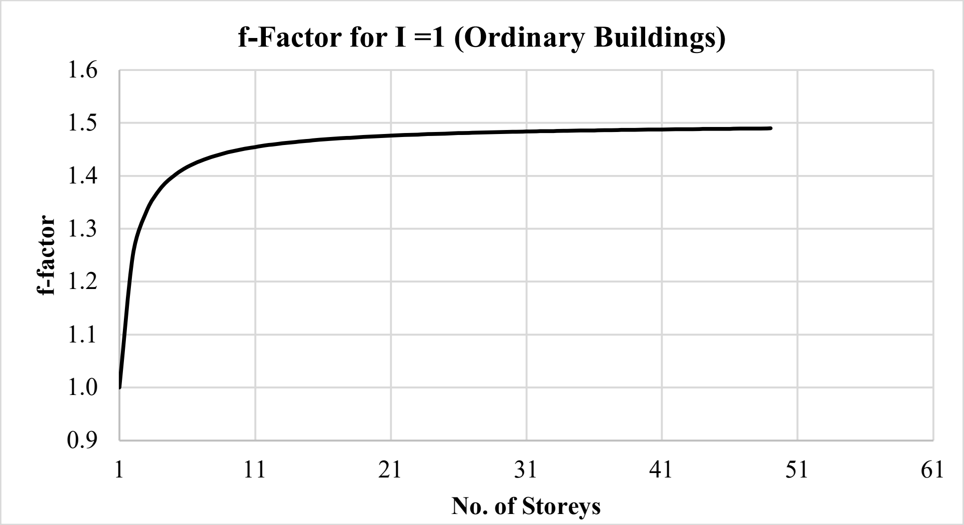

Figure 2. Dependence of f-factor in α_{district} on Number of Storey (I =1)

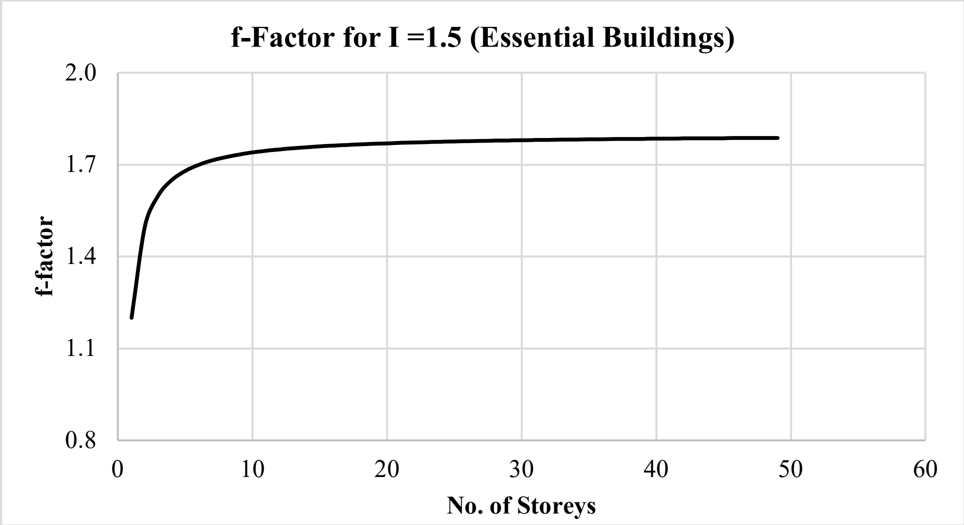

Figure 3. Dependence of f-factor in α_{district} on Number of Storey (I =1.5)

The findings reveal that the amplification factor rises very fast in the first five to eight storeys and then tends to level off to an asymptotic value as represented in Figure 2. With Ip = 1, the factor reaches a stabilization value of ($f_{\text{approx}} = 1.4 - 1.5$), whereas with Ip = 1.5

the stabilization value is (f_{approx} = 1.7 - 1.8). The height of the building beyond this height-range leads to little changes in the amplification factor. This behavior establishes that the height term significantly varies only towards the extremely low-rise structures and is all but constant over most of the mid to high rise structures.

Engineering wise, this observation supports the fact that explicit height dependency should be removed in applications at a national scale. It would be confusing to hold on to the complete height-dependent formulation, which would not contribute to any significant improvements in the accuracy of regional vulnerability assessment. Using a constant envelope figure is thus a logical simplification that does not change the physical meaning of ASCE 7-16/7-22 but makes it practical.

3.2 Distribution of $\boldsymbol{\alpha}_{district}$ of Ordinary Buildings (I = 1.0) (District-Wise).

$\alpha_{district}$ values of all the provinces and soil classes were calculated by using simplified formulation. Table 2 shows representative of some of the selected districts which cover low, moderate, and high seismic areas and the full national dataset is in Appendix A (Table A1).

In the case of ordinary buildings, there is a great deal of regional variation in the value of $\boldsymbol{\alpha}_{district}$ values, with a range between approximately 0.2 in the low-seismic areas of southern Punjab and interior Sindh, and values up to the high values of over 2.3 in the northern areas of Pakistan and some of Baluchistan. The greatest values are experienced in earthquake prone areas of Gilgit Baltistan, Azad Kashmir, Khyber Pakhtunkhwa, and other earthquake-prone regions, e.g. Sialkot, Narowal, Abbottabad, Astore, and Lehri.

The $\boldsymbol{\alpha}_{district}$ values range between 0.23-1.96 for Soil Class (A, B and D) while for Soil Class C the range is (0.3-2.3). Despite these, the predicted OOP forces remain large enough to initiate the brittle out-of-plane failure of unreinforced masonry infills in even these regions, especially in thin panels, or where a building has construction gaps.

Table 2. Representative $\alpha_{district}$ values for ordinary buildings (Ip = 1) for selected districts and soil classes

Province	District	α_A	α_B	α_C	α_D
Punjab	Lahore	0.392	0.441	0.637	0.68992
Punjab	Sialkot	1.544	1.737	2.316	1.93
KPK	Peshawar	0.672	0.756	1.008	0.97776
GB	Astore	1.464	1.647	2.196	1.83
Balochistan	Quetta	0.736	0.828	1.104	1.04144

(Full dataset for all districts provided in Appendix A.)

3.3 District-Wise Distribution of $\boldsymbol{\alpha}_{district}$ for Essential Buildings (I = 1.5)

Table 3. Representative α_{district} values for essential buildings (Ip = 1.5) for selected districts

Province	District	α_A	α_B	α_C	α_D
Punjab	Lahore	0.4704	0.5292	0.7644	0.827904
Punjab	Sialkot	1.8528	2.0844	2.7792	2.316
KPK	Abbottabad	1.4976	1.6848	2.2464	1.872
GB	Astore	1.7568	1.9764	2.6352	2.196
Sindh	Karachi South	0.7776	0.8748	1.1664	1.143072

(Full dataset provided in Appendix B.)

3.4 Comparison Between Demand and Experimentally Validated Capacity

The simplified factors of demand were computed and then compared with the OOP capacity model that was experimentally tested and then with generic sizes of wall. Annex E and Annex F show the Maps of factor of safety (FOS) of typical infill geometries (L x H x t) = (4 ± 1m) x (3m) x 9″ and 4″). Annex C & D show their individual FoS values.

In the 4.5-inch thick infills, most districts show FOS of less than 1.0 of ordinary buildings and essential buildings. In the case of 9-inch thick infills the safety is enhanced, but in the north of Pakistan and other high seismic areas, FOS is smaller than unity of buildings of necessity (essential building of I p =1).

4. Conclusions

The proposed study in this paper was to provide a simplified and nationally scalable process of determining the seismic out-of-plane (OOP) demand and capacity of mortar-jointed masonry infills in Pakistan. The ASCE 7-16 height-dependent demand equation has been strictly simplified into a single district-based factor, α_{district}, in such a way that OOP demand can be computed directly as F_{OOP}. The height-dependent demand equation defined by ASCE 7-16 has been reduced to a single factor, which is the α_{district}, with which OOP demand can be calculated as $F_{OOP} = \alpha_{\text{district}}\ W p$.

Parametric assessment of the height amplification term indicated that the demand factor quickly converged after about eight storeys in both cases I p. Parametric analysis of the height amplification term demonstrated that the demand factor converging rapidly with more than eight storeys in either case of I p = 1.0 and I p = 1.5. This justifies the application of an envelope based constant factor in regional and national application.

Across Pakistan, there was a high level of spatial variability of α_{district} values at the district level. The largest demand rates were found in Gilgit-Baltistan, Azad Kashmir, northern

Khyber Pakhtunkhwa and central Baluchistan. Non-negligible OOP demand was registered even in moderate seismic areas.

Experimental testing using four points demonstrated that the Ricci et al. capacity formulation was correct in predicting the OOP strength of the Pakistani brick infillings made locally. It is a model thus useful in national capacity assessment.

Comparisons of demand with capacity show that 4.5-inch infills are very unsafe in the majority of the districts and especially in Soil Class C and D. Infills like those which are 4.5 inches in thickness are not safe in high seismic areas and when a building is a necessity. The suggested structure offers the OOP seismic demand model that was first resolved on the district level in Pakistan.

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Appendix A

Table A1: Complete α_{district} dataset for all districts of Pakistan, soil classes A-D, (Ip = 1.0) and could be found at (https://doi.org/10.5281/zenodo.18442454).

Appendix B

Table B1: Complete α_{district} dataset for all districts of Pakistan, soil classes A-D, (Ip = 1.5) and could be found at (https://doi.org/10.5281/zenodo.18442454).

Appendix C

OOP-FOS for low-rise buildings (Generic Size) for soil class (A-D) for each district of Pakistan could be found at (https://doi.org/10.5281/zenodo.18442242).

Appendix D

OOP-FOS for High-rise (8th Storey & Above) buildings (Generic Size) for soil class (A-D) for each district of Pakistan could be found at (https://doi.org/10.5281/zenodo.18442242).

Appendix E

OOP FoS Map for low rise buildings for each Soil Class (A-D) for each District of Pakistan and could be found at (https://doi.org/10.5281/zenodo.18442628).

Appendix F

OOP FoS Map for high rise buildings for each Soil Class (A-D) for each District of Pakistan and could be found at (https://doi.org/10.5281/zenodo.18442713).

List of Acronyms

Acronym	**Full Form**
ASCE	American Society of Civil Engineers
ASCE 7-16	Minimum Design Loads and Associated Criteria for Buildings and Other Structures
ASCE 41-17	Seismic Evaluation and Retrofit of Existing Buildings
BCP	Building Code of Pakistan
BCP-2021	Building Code of Pakistan 2021
DOF	Degree of Freedom
EEC	Earthquake Engineering Center
FE	Finite Element
FEMA	Federal Emergency Management Agency
FEMA 306	Evaluation of Earthquake Damaged Concrete and Masonry Wall Buildings
FOS	Factor of Safety
GB	Gilgit-Baltistan
IP / I_p	Importance Factor
KPK	Khyber Pakhtunkhwa
NSE	Non-Structural Element
OOP	Out-of-Plane
IP (loading)	In-Plane
RC	Reinforced Concrete
RP / R_p	Response Modification Factor
SDS	Design Spectral Acceleration at Short Period
SS	Mapped Spectral Acceleration at Short Period
S1	Mapped Spectral Acceleration at 1-Second Period
TMS 402/602	The Masonry Society Building Code Requirements and Specification
URM	Unreinforced Masonry
Wp / W_p	Weight of Non-Structural Component
z/h	Relative Height Ratio in Building
αdistrict	District-Specific Seismic OOP Demand Coefficient
FOOP	Out-of-Plane Seismic Force
Pexp	Experimental Peak Load
$P_{analytical}$	Analytical Predicted Load

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