RESPONSE OF TYPICAL BUILDINGS TO LONG-DISTANCE EARTHQUAKES

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SUMMARY

Singapore is a city-state located in a low seismicity area with mild winds. The country is a classic example of low seismic hazard and high exposure scenario. It is about 400 km away from a highly active earthquake belt, the Sumatra subduction complex, where great earthquakes have occurred in the past. Twenty-seven earthquakes have been reportedly felt in Singapore since the British settlement in 1819. The frequency of these felt events seems to be rising with time as the country develops. The response of a building to long-distance earthquakes is dependent on the type of structural systems and the local geological conditions. Tall buildings founded on Quaternary deposit are particularly apt to respond to distant earthquakes and give evidence to the phenomenon of site dependent building response in Singapore to the long-distance Sumatra earthquakes. A set of tentative design spectra for Singapore has recently been proposed. Elastic response of one of the most common types of high-rise residential buildings to the tentative design spectra is reviewed.

INTRODUCTION

Singapore is a city-state located off the southern tip of Malay Peninsula. The country has a population of about 3 million and an area of about 600 km^2. Although small in size, the country's gross domestic product per capita was US$ 22,300 in 1994, among the highest in Asia. Most people live in high-rise buildings due to land shortage. The country is located in a low seismicity area with mild winds. Since there has never been any earthquake damages in the country, buildings in general are not specifically designed against the horizontal earthquake loading. Therefore, the city is a classic example of low seismic hazard and high exposure scenario. A set of tentative design spectra for different geological conditions in Singapore has recently been proposed [Pan and Sun, 1996a]. This paper examines the elastic response of one of the most common types of high-rise residential buildings subjected to the tentative design spectra.

REGIONAL SEISMICTY

Although Singapore and Peninsular Malaysia are in an aseismic area, an active earthquake belt, comprising the Sumatra Fault and the subduction zone, is only 350 km away at the closest point. Sumatra is part of the Indonesia island arc. The India-Australia plate subducts below the Eurasia plate along this arc at a rate of about 67 mm year [Demets et al., 1990]. The displacement between the two plates is partly accommodated by sudden movements, which cause numerous earthquakes. Figure 1 shows the epicentre locations of earthquakes occurring in this region between 1960 and 1994. In the figure, the large circle centred at Singapore with 500 km radius is included for reference, and the size of small circles indicates the earthquake magnitude. Very large earthquakes have been generated along the interface between the two plates. The great earthquake in 1833 was estimated to have a moment magnitude (Mw) of 8.7 to 8.8 and was believed to have caused a 500 km long rupture along the interface [Newcomb and McCann, 1987].

On the oceanic side of the trench, bending of the oceanic lithosphere prior to subduction also generates large earthquakes. On the land side, a dextral strike-slip fault, the great Sumatra Fault, is another source of numerous earthquakes [Katili and Hehuwat, 1967]. The Sumatra Fault is more than 1,500 km long and runs through the

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entire length of Sumatra, coinciding with the Barisan Mountain belt. At its closest point, the fault is about 350 km away from major cities on the Malay Peninsula such as Kuala Lumpur, the capital of Malaysia, and Singapore. The earthquake occurring on the Sumatra Fault on 17 May 1892 caused wide-spread shakings in Singapore [Bolt, 1977].

Most earthquakes in Sumatra are of shallow to intermediate focal depth. Deep events are very unusual. Of every 200 earthquakes found within the Sumatra area, only one is deeper than 300 km, and the deep events are all in the southern Sumatra area close to Java. This is in contrast to Java where numerous earthquakes are deeper than 600 km. The lack of deep seismic activity in Sumatra indicates that the subducting plates do not penetrate deeply into the mantle. The relatively shallow penetrating subducted slab produces a strong coupling between the overriding and the subducting plates in Sumatra, and large or great earthquakes can thus occur in the region. In Java, the reverse is true. Uyeda and Kanamori (1979) classified subduction zones into the Mariana type and the Chilean type. In the former case, the subducted slab descends almost vertically deep into the mantle, and the overriding and the subducting plates are weakly coupled, causing back-arc opening. In the latter case, the subducted slab moves at shallow angle, and the overriding and the subducting plates are strongly coupled, causing very large earthquakes. It is reasonable to speculate that Sumatra is more of the Chilean type while Java resembles the Mariana type more. There has never been a well-determined great earthquake in Java, while some of the greatest earthquakes had occurred in Sumatra [Newcomb and McCann, 1987].

The size, location and timing of earthquakes are generally erratic. The study by Sun and Pan (1995b) showed the strongest earthquakes that have been reported in Sumatra in each decade since 1830, after the British settlement was established in 1819 and that there have been no great earthquakes in the last half century. The two greatest earthquakes Mw = 8.7 to 8.8 in 1833 and Mw = 8.4 in 1861 [Newcomb and McCann, 1987] that have been determined so far both occurred in the previous century, when there were practically no high-rise structures or reclaimed land. Therefore it is not surprising that historically earthquake hazard has hardly been an issue for the Malay Peninsula, and earthquake resistant design has been required only for some of the more important structures, for example the Penang Bridge [Chin, 1988].

Assuming a uniform seismicity for the rectangular area over Sumatra, the statistics of Sumatra earthquake activities were investigated by Sun and Pan (1995b). There is a high probability of major ($m > 8.0$) earthquakes occurring in the Sumatra region. However, it is understood that the earthquake catalogue for the region is rather incomplete [Pan and Sun, 1996b].

Although there has never been any earthquake damages to Peninsular Malaysia and Singapore, ground tremors were reportedly felt in these areas for many times, and the incidents have increased in number significantly over the last three decades. The first systematic documentation on the seismicity of Peninsular Malaysia and Singapore was done by the Southeast Asia Association of Seismology and Earthquake Engineering (SEASEE) [Leyu et al., 1985]. Pan and Sun (1996b) updated SEASEE's report with respect to the earthquake events reportedly felt in Singapore between 1833 and 1995. Some uncertain old events were removed from SEASEE's list, and the new ones from 1985 to 1995 were added. The Modified Mercalli intensity (MMI) for some events in Singapore was reassigned. There have been no seismographic stations in Singapore, and the ground motion reports are therefore based solely on local newspapers and the anecdotal history of Singapore [Buckley, 1984]. Epicentres of the Sumatra earthquakes responsible for the felt tremors in Singapore generally fall around a circle of 500 km radius centred at Singapore.

SURFACIAL GEOLOGY AND BUILDING RESPONSE TO GROUND TREMORS

The observation that high-rise buildings in some areas in Singapore were shaken more frequently than other types of structures in the same area and structures in other areas warrants further elaboration. The main island of Singapore may be divided into four geological groups: (i) Bukit Timah Granite and Gombak Norite, (ii) Jurong Formation, (iii) Quaternary deposit comprising Old Alluvium and Kallang Formation, and (iv) Reclaimed Land. Besides the main groups, there is the Sajahat Formation, which is found in some small areas.

The Bukit Timah Granite and Gombak Norite occupy the central and the central north parts of Singapore. They are covered by residual soil, with depth ranging from 10 to 60 meters. The Jurong Formation forms the west and the southwest of the Singapore Island. It consists of sedimentary rocks of Upper Triassic and lower to middle Jurassic age. The rocks include various types of mudstone, sandstone, shale, conglomerates and newly discovered limestone. In the western part, the sedimentary rocks are mostly covered by a weathering layer of a

few meters to tens of meters. In the southern part, they are partly covered by the young Quaternary deposits called Kallang Formation.
The eastern part of the Island is covered by the Old Alluvium and the Kallang Formation, the two major Quaternary units, underlain by the extension of the Bukit Timah granite [PWD, 1976]. The Old Alluvium consists of loose sand and fine gravel with silt and clay lenses. It is of Pleistocene age and covers the eastern part of Singapore. The Kallang Formation consists of Holocene sediments of marine, alluvial, littoral and estuarine origin. It is distributed in many parts of Singapore but most consistently in the southeastern coast. The thickness of these Quaternary deposits varies, at some sites more than 185 meters. But at other sites, the Granite can be shallower or even close to the surface. The island is surrounded by reclaimed land, especially along its southern coast. Reclaimed land accounts for about 10% of Singapore's total area as of today, and is expected to increase.

The distribution of the Kallang Formation and the reclaimed land coincides with the area where buildings reportedly responded to the long-distance Sumatra earthquakes. It is well-known that tall buildings founded on soft soils are likely to respond to long-distance major earthquakes, an extreme example of which is the Mexico City earthquake of 1985 [Booth et al., 1986]. Soft deposits can amplify low frequency earthquake waves significantly. The engineering properties of these young deposits are therefore of importance. A quick survey of the amplification potential of surfacial materials has been performed by micro-tremor measurements. The measured data were analysed using the method of Nakamura (1989). The results show that the natural frequency is below 2.5 Hz for Kallang Formation and reclaimed land, and above 2.5 Hz for other areas.

There were practically no high-rise buildings in Singapore until the 1970s. Beginning in 1971, only high-rise buildings in Singapore reportedly responded to the long-distance Sumatra earthquakes. There have been ten such incidents since then. It is well known that tall buildings founded on soft soils are likely to be more responsive to long-distance major earthquakes, as exemplified by the Mexico City earthquake of 1985. Singapore's high-rise buildings were mostly constructed during the last 30 years. The 24 buildings that have reportedly responded to some of the recent long-distance Sumatra earthquakes and are predominantly high-rise reinforced concrete structures. The responding buildings are mostly located in the southeast of Singapore, where the Kallang Formation is most extensively distributed.

TENTATIVE DESIGN SPECTRA

Singapore's current building code has been formulated largely on the basis of British Standards, e.g. BS 8110 code [BSI, 1985b]. The BS 8110 code does not have any provision for seismic loading. It however requires that, for structural robustness, all buildings should be capable of resisting a notional design ultimate horizontal load, applied at each floor level simultaneously, equal to 1.5% of the characteristic dead weight of the structure. The design wind load should therefore not be taken as less than this value. Given the moderate design wind speed of 30 m/s in Singapore, however, the notional horizontal load is generally greater than the wind loading for most buildings and thus the governing lateral design load.

Figure 2 shows the set of tentative design spectra that have been developed for the gr1ound surface of rock, soil, and soft soil sites in Singapore [Pan and Sun, 1996a]. The tentative design spectra represent the characteristics of surface ground motions in Singapore resulting from the long-distance Sumatra earthquakes. The exceedance probability of the design spectra is 10% in 50 years. The maximum value of the three acceleration response spectra is 0.1 g. The corner period where the spectral acceleration begins to reduce is located at 0.2 s, 0.5 s, and 1.0 s, respectively, for the rock, soil and soft soil sites. The elastic seismic response of a typical building in Singapore to the tentative design spectra in the two horizontal directions will be investigated in this study.

THE TYPICAL BUILDING

One of the most common types of buildings in Singapore is a 15-story medium-rise reinforced concrete residential building. It typically has a narrow rectangular plan (94.5 m $\times$ 11.0 m) of approximately 1,040 m^2 in area. Figure 3 shows elevation views and plan of the typical building. The inter-storey height of the building is 2.8 m except the first story where the clear height is 3.6 m. The total height of the building is therefore 42.8 m.

The structural system of the typical building comprises reinforced concrete frames and shear walls. In the transverse direction, it consists of a series of two-bay frames with rectangular columns of a large aspect ratio (0.3 m $\times$ 1.2 m), resulting in a relatively low out-of-plan stiffness along the longitudinal direction of the building.

The beam sizes are typically 0.3 m × 0.5 m or 0.3 m × 0.6 m. The thickness of floor slabs is 0.125 m and that of the shear walls is 0.2 m. The modulus of elasticity of concrete material is taken as 24.8 MPa while the Poisson's ratio is taken as 0.20. The estimated weight of each story is 9,800 kN.

The partition walls in a typical high-rise residential building are usually constructed with traditional clay bricks of 115 mm thickness with mortar joints. While the internal masonry partition walls are of full height, the exterior masonry in-fill walls along the corridor are generally of half height, leaving the upper part for window openings. For comparison with the results of a bare-frame, the stiffness of the masonry in-fill walls is included via panel elements with material properties taken from BS 5628 (1985a). The masonry properties used in the analysis are unit weight of 21 kN/m^3, modulus of elasticity of 15 MPa, and Poisson's ratio equal to 0.15.

Dynamic Characteristics

The first three natural periods and modal participation factors of the typical high-rise residential building are summarised in Table 1. The table shows that by including the stiffness of masonry in-fill walls, the fundamental period shortens from 1.57 s to 0.69 s. The decrease in the fundamental period is accompanied by a switch in the direction of fundamental mode from the longitudinal (x) direction to the transverse (y) direction.

Table 1: Periods and modal participation factors of the typical building

	Without masonry in-fill walls				With masonry in-fill walls			
Mode No.	Period (s)	Participation Factors			Period (s)	Participation Factors		
		X	Y	Z-rot.		X	Y	Z-rot.
1	1.57	109.6	-0.4	-73.8	0.69	4.1	-98.3	682.0
2	1.01	1.5	-82.0	1596.2	0.61	7.1	24.4	2722.4
3	0.86	3.4	57.7	2258.7	0.52	-116.9	-2.2	196.5

While the mode shapes indicate the existence of torsional response, the primary response of the typical building is translational. In addition, as the masonry in-fill walls are added to all stories above the first story, the lateral stiffness of the typical building changes abruptly over the second story level, resulting in a soft first story and consequently the discontinuity at the second story level.

SEISMIC RESPONSE

For the typical high-rise residential building subjected to the ground motions represented by the three tentative design spectra, Table 2 summarises the maximum inter-story drift ratios at the centre of mass of the floor diaphragms. The table shows that the soft soil ground motion results in the maximum inter-story drift ratio. However, these inter-story drift ratio are small compared with the UBC value of 0.004 [ICBO, 1994]. Figures 4 and 5 show the profiles of the maximum displacements along the longitudinal (x) and transverse (y) directions of the typical high-rise building, respectively. The figures show that the maximum displacement in both directions at the roof level results from the ground motion for soft soil sites. This demonstrates to some extent the effect of soft soil amplification coupled with the phenomenon of site-dependent building response.

The maximum seismic demands of the typical building subjected to the tentative design spectra can be expressed in terms of the base shear coefficients. Responding to the ground motion for soft soil sites, the base shear coefficient for the building without the masonry in-fill walls ranges between 0.037 in x-direction and 0.054 in y-direction. The base shear coefficient increases substantially to between 0.084 in x-direction and 0.061 in y-direction when the masonry in-fill walls are included. These values, though small compared with the total base shear strength, are much larger than the notional horizontal load specified as 1.5% of the characteristic dead weight in the BS 8110 Code [BSI, 1985b].

Detailed analysis of the shear force capacity of individual members shows that without considering the masonry in-fill walls, the shear force capacity of two shear walls in the longitudinal (x) direction at the first story is exceeded. When the masonry in-fill walls are included in the model, there is a substantial increase on the shear force demand. The results show that not only the capacity of these two shear walls but also that of four additional columns at the first story is exceeded.

Table 2: Maximum inter-storey drift ratios of the typical building

Site Conditions	Rock Site		Soil Site		Soft Soil Site	
Direction	X	Y	X	Y	X	Y
Without Masonry In-fill Walls	0.00079	0.00046	0.00129	0.00118	0.00157	0.00157
With Masonry In-fill Walls	0.00039	0.00029	0.00064	0.00061	0.00083	0.00068

CONCLUSIONS

Elastic seismic response of one of the most common types of high-rise residential buildings in Singapore to the tentative design spectra for rock, soil, and soft soil sites has been reviewed. The main observations on the elastic seismic response of the typical building are summarized as follows:

(1) Among the ground motion excitations represented by the set of tentative design spectra, the spectrum of soft soil site has produced the largest displacement response, inter-story drift ratio and base shear coefficient. This demonstrates to some extent the amplification effects of soft soil coupled with the phenomenon of site-dependent building response.

(2) The maximum value of inter-story drift ratio is smaller than the value of 0.004 as specified in the 1994 UBC code.

(3) Adding the masonry in-fill walls to the typical building results in a soft first story and thus a substantial increase in the base shear coefficient.

(4) The seismic demand expressed in terms of the base shear coefficient ranges from 0.024 to 0.084. While these values are small, they are larger than the notional horizontal load, specified for structural robustness in the BS 8110 code as 1.5% of the characteristic dead weight.

(5) In the longitudinal direction of the typical building, when subjected to the postulated soft soil ground motion, the capacity of two shear walls at the first story is exceeded. When the stiffness of the masonry in-fill walls is included, the capacity of four additional columns at the first story is also exceeded.

REFERENCES

Bolt, B.A., (1977), *Seismicity and Seismic Intensity Study (Penang-Wellesley Crossing, Malaysia)*, Unpublished report.

Booth, E.D., Pappin, J.W., Mills, J.H., Degg, M.R., and Steedman, R.S., (1986), *The Mexican earthquake of 19th September 1985*, A Field Report by EEFIT, The Institution of Civil Engineers, London.

BSI, (1985a), *Materials and Components*. British Standard, Code of practice, BS 5628: Part 1, London.

BSI, (1985b), *Structural Use of Concrete*, Part 1. Code of Practice for Design and Construction, BS 8110: Part 1, British Standards Institute, London.

Buckley, C.B., (1984), *An Anecdotal History of Old Times in Singapore, 1819 - 1867*, Oxford University Press, Cambridge.

Chin, F.K., (1988), *The Penang Bridge: Planning, Design and Construction*, Ketua Pengarah, Lembaga Lebuhraya Malaysia, Kuala Lumpur.

Demets, C., Gordon, R.G., Argus, D.F., and Stein, S., (1990), "Current plate motions", *Geophys. J. Int.*, 101, p. 425-478.

Katili, J.A. and Hehuwat, F., (1967), "On the occurrence of large transcurrent faults in Sumatra, Indonesia", *J. Geoscience*, Osaka City Univ. 10, p. 5-17.

Leyu, C.H., Chang, C., Arnold, E.P., Kho S.L., Lim, Y.T., Subramanian, M., Ong, T.C., Tan, C.K., Yap, K.S., Shu, Y.K., and Goh, H.L., (1985), *Series on Seismology, Volume III - Malaysia*, Southeast Asia Association of Seismology and Earthquake Engineering.
Nakamura, Y., (1989), "A method for dynamic characteristics estimation of subsurface using micro-tremors on the ground surface", *QR of ERI*, 30, No. 1., p. 25-33.
Newcomb, K.R. and McCann, W.R., (1987), "Seismic history and seismotectonics of the Sunda Arc", *J. Geophys. Res.*, 92, p. 421-439.
Pan, T. C. and Sun, J. C. (1996a), *Estimate of Free-Field Response Spectra*, Technical Report No. 4, NTU/PWD Joint Research Project.
Pan, T.-C., and Sun, J., (1996b), "Historical earthquakes felt in Singapore", *Bull. Seism. Soc. Amer.*, 86, p. 1173-1178.
PWD, (1976), *Geology of the Republic of Singapore*, Public Works Department, Government of Singapore.
Sun, J. and Pan, T.-C., (1995a), "Seismotectonics of Sumatra and its relevance to Peninsular Malaysia and Singapore", *J. Southeast Asia Earth Sciences*, 12, p. 105-111.
Sun, J. and Pan, T.-C., (1995b), "The probability of very large earthquakes in Sumatra", *Bull. Seism. Soc. Amer.*, 85, p. 1226-1231.
Uyeda, S. and Kanamori, H., (1979), "Back-arc opening and the mode of subduction", *Tectono-physics*, 84, p. 1049-1061.

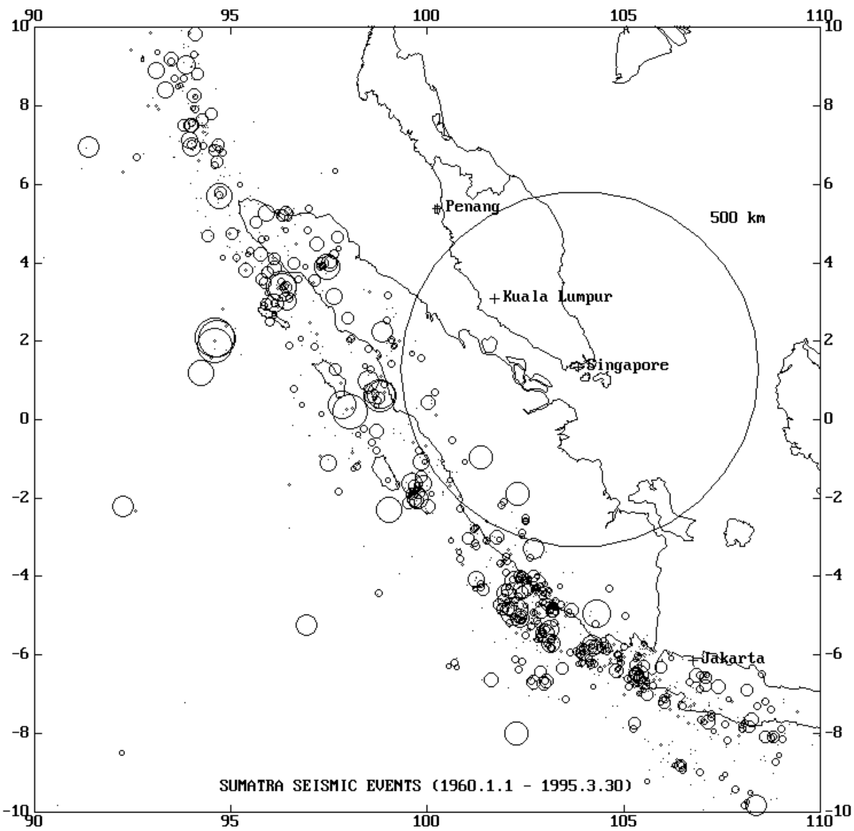

Figure 1: Epicentre locations of earthquakes in Sumatra region (1960.1.1 - 1995.3.30)

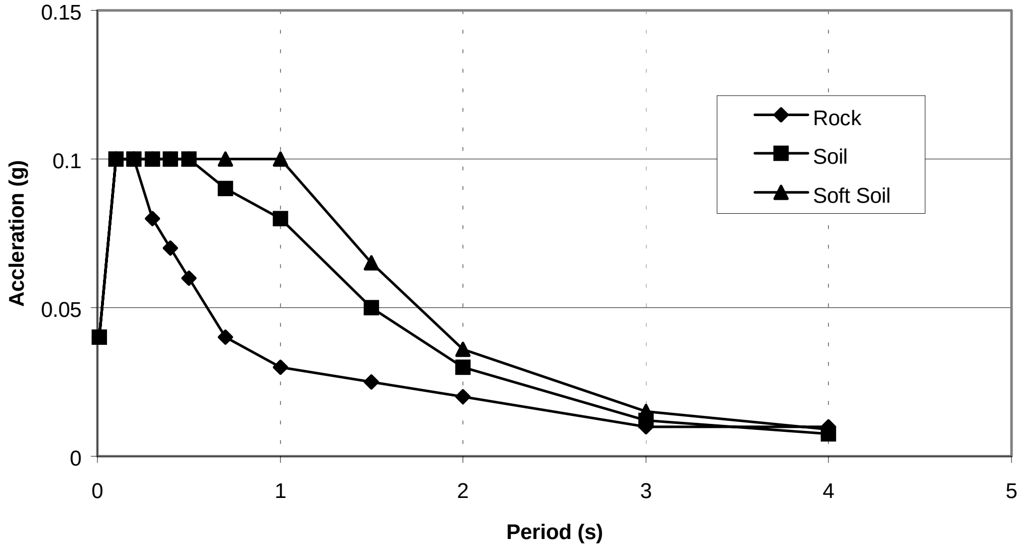

Figure 2: Tentative design spectra for rock, soil and soft soil sites in Singapore

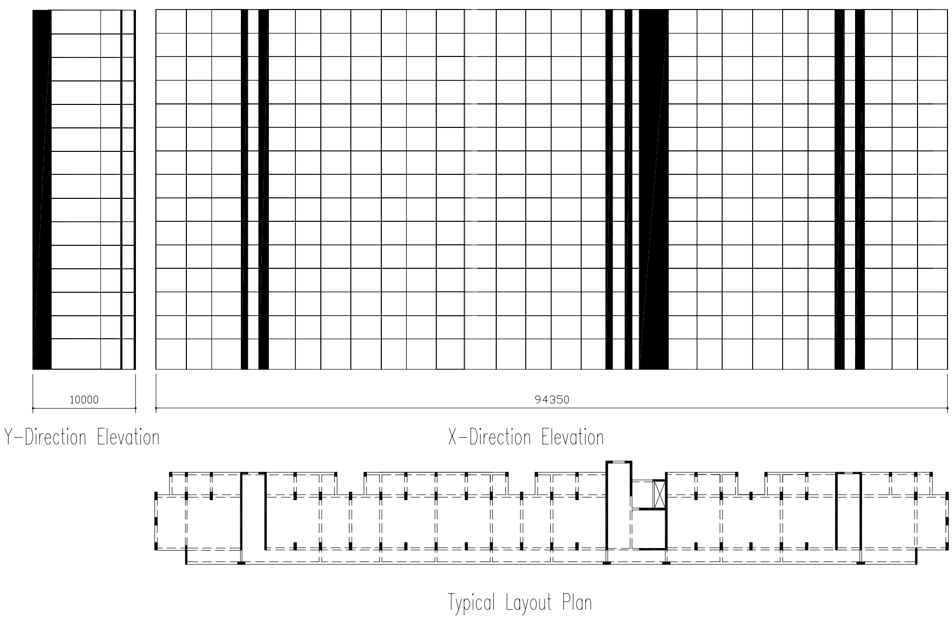

Figure 3: Elevation views and typical floor plan the typical building

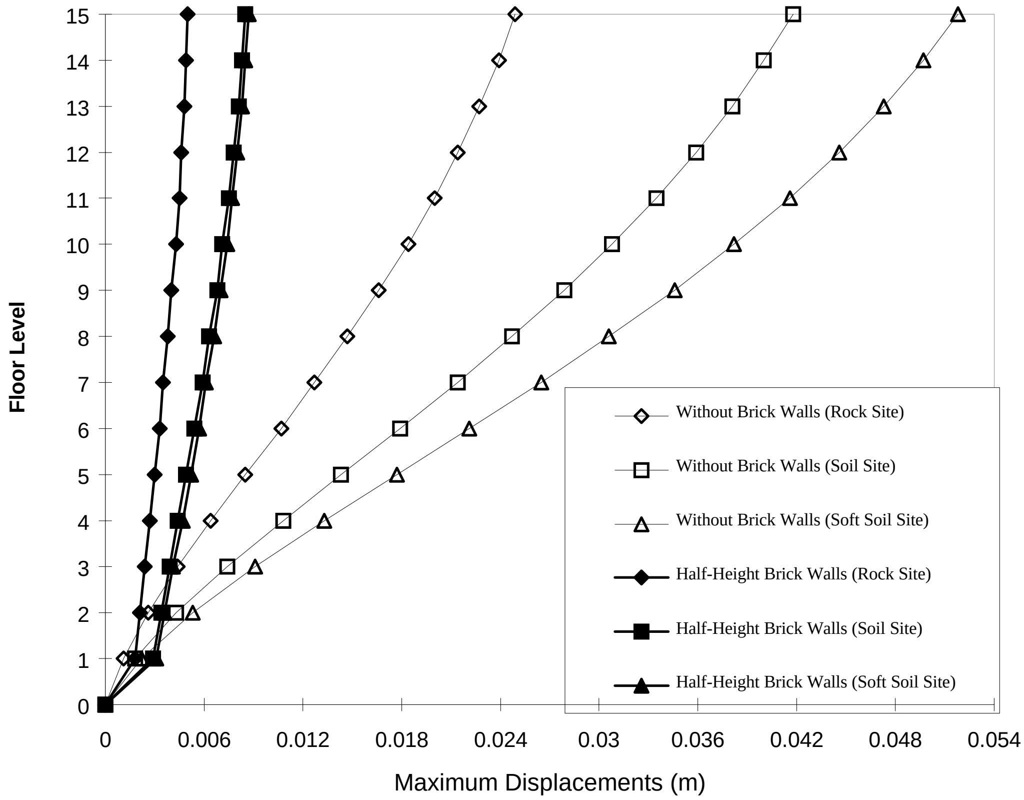

Figure 4: Maximum displacements in the longitudinal direction of typical building

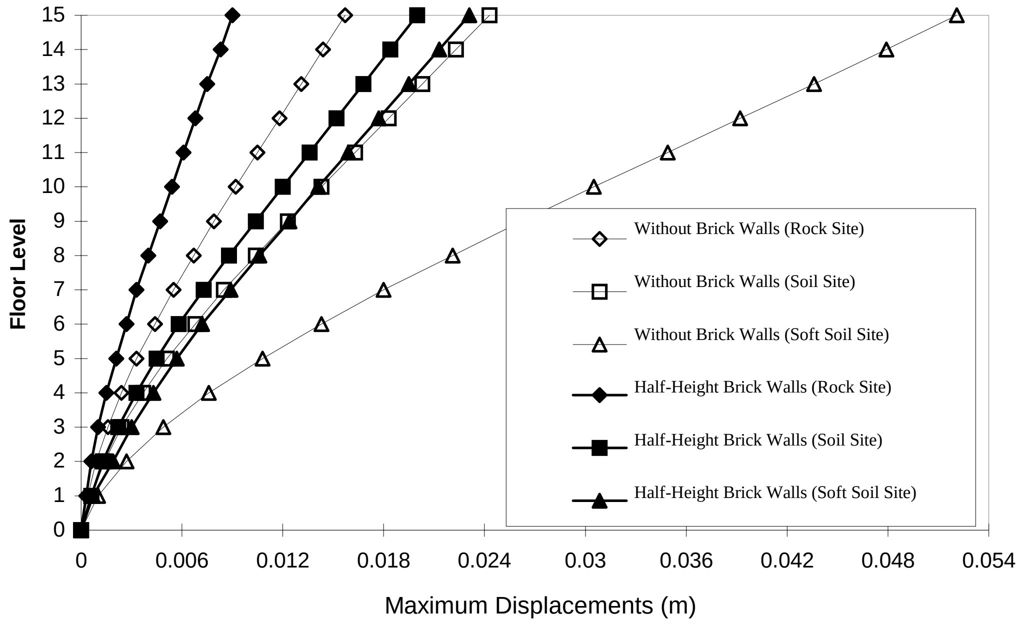

Figure 5: Maximum displacements in the transverse direction of typical building