Impact of Natural Period and Epicentral Distance on Storey Lateral Displacements

S. Dorbani, M. Badaoui, D. Benouar

***Abstract*—**The goal of the paper is to highlight the effect of the building design and epicentral distance on the storey lateral displacements, for several reinforced concrete buildings (6, 9 and 12 stories). These structures are subjected to seismic accelerations from the Boumerdes earthquake (Algeria, May 21st, Mw = 6.8). Using the response spectrum method (modal spectral approach), the analysis is performed in both longitudinal and transverse directions. The building design is expressed through the fundamental period and epicentral distance is used to represent the earthquake effect variation on storey lateral displacements and interstory drift for the considered buildings.

***Keywords*—**Epicentral distance, interstory drift, lateral displacement, natural period, reinforced concrete buildings.

I. INTRODUCTION

EARTHQUAKES are definitely the most destructive natural disasters in urban areas. They involve the destruction of entire cities and killing thousands of peoples, and huge economic losses [1], [2].

A ground motion can apply large lateral forces on the structures, which generate lateral displacements in response to those forces. For multi-storey building two responses in terms of displacement can be defined: lateral displacement which is the predicted movement of a structure under lateral loads, and story drift as the difference in lateral displacement between two adjacent stories.

Seismic codes require that the designer has to assess the effects of these deformations on both structural and nonstructural elements and the movements can affect adjacent structures.

Both of structural and nonstructural elements should be designed to allow the expected movement of the structural systems which are subjected to lateral displacement due to seismic forces. [3].

During an earthquake, neighboring building or separated structures of the same building can pound against each other if they do not have the right separation distance.

This phenomenon can be worse, if the adjacent structures floors are not co-planer, the pounding of the first structure floor on the column of the other building provides large stresses due to shears forces and bending moments, and can occasion the building collapse [4]. However, when adjacent structures have coplanar floors, pounding will tend to damp out vibrations and reduce the responses of the two structures which make it more difficult to resonate with the earthquake. For this reason, estimating the maximum lateral displacement of the structures in the wake of massive earthquakes is considered to be widely important for seismic design. These include: estimating minimum separation joint width to avoid pounding, estimating maximum storey drifts to avoid destruction of non-structural elements and performance of Pdelta analysis [5].

Fig. 1 Buildings have undergone a whiplash during Mexico 1985 earthquake

For economic reasons, recent seismic codes allow structures during earthquake to undergo inelastic deformations, which makes the corresponding lateral force lower than the force required force to maintain the structure in the elastic range [6].

On Wednesday, May 21, 2003 at 19:44:40 (GMT +1), the regions of Algiers and Boumerdes, northern Algeria, were subjected to a destructive earthquake of a magnitude of (Mw = 6, 8); that claimed about 2300 human lives and about 11,000 injured people. This makes it the worst seismic event since the El Asnam. October 10, 1980, Ms = 7.3 [7]-[10].

Early reports indicate that damages caused by earthquake are due to several factors: The structural failures, namely the poor quality of construction materials, structural failures and shortcomings due to noncompliance with earthquake codes are also major factors contributing to the extent of damage. In addition, the soil effects played an important role in damage for various forms such as liquefaction, loss of bearing capacity, subsidence and lateral spreading [10].

Experience has shown that the structures' behaviors during an earthquake depend on several parameters. Buildings of

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different construction materials or configurations will respond differently under the same earthquake, some may survive while others collapse [11]-[14].

To highlight the effect of the building height, its fundamental period and the site epicentral distance on building lateral displacements, various reinforced concrete buildings are subjected to seismic acceleration recorded during the Boumerdes earthquake (Algeria May 21, 2003). The seismic responses of buildings are carried by the method of response spectrum [11]-[14].

Fig. 2 Building damages observed in the city of Boumerdes (photo from CSEM-EMSC September 2003)

II. Structural Data

The modelled buildings are reinforced concrete various heights (6, 9 and 12 storeys) with three different floors geometry: symmetrical (SB), Mono symmetrical (MB) and unsymmetrical (UB)). Nine building types are considered and noted: 06 SB, 06MB, 06UB, 09 SB, 09MB, 09UB, 12 SB, 12MB, 12UB. The dimensions of the standard plan buildings are 22.7 m x 13.75 m. with a story height of 3m. The structural systems adopted are portal frame and shear walls in both directions. The columns, beams, slabs and shear walls are designed according to requirement given in the Algerian earthquake Regulation RPA 99 / 2003 version [15]. The cross sections of the columns have been changed after the 3rd storey for the 6 stories buildings, and changed after the 4th for the buildings 9 and 12 levels, a further change of dimensions beyond the 8th story for 12 stories buildings. The structural systems of the various buildings are gantry with shear walls in both directions, in this case the RPA99/2003 recommend the value of 5 for the coefficient of overall behaviour of the structure R.

III. Modelling

To assess the structural response of buildings, a seismic elastic analysis is performed by the spectral response method (spectral modal approach) using the software ETAB 9.5 (2008) [16]. This analysis is done separately in the longitudinal and transverse direction. However, only the maximum response's values are presented in this paper.

The finite element model does not consider the soil-structure interaction; therefore, the degrees of freedom of the base nodes are fixed, while the other nodes are free.

The columns and beams are modelled with frame elements and shell elements for shear walls. Finally, the slabs are considered as rigid diaphragms in each level. In this analysis, the damping value is 5% for all modes; t his Young's modulus and weight density of concrete are respectively 28000MPa and 25kN/m^3. The parameters of the dynamic response of structures involved in this study are:

- Fundamental period
- Storey displacement
- Interstory drift
- Site conditions

IV. Analysis of the Results

Modal spectral method is dynamic analysis of a structure under the effect of an earthquake represented by a response spectrum. It allows to search for each vibration mode, the maximum effects in the structure caused by seismic forces - represented by a response spectrum calculation-. These effects are then combined to obtain the response of the structure [15].

A. Fundamental Periods

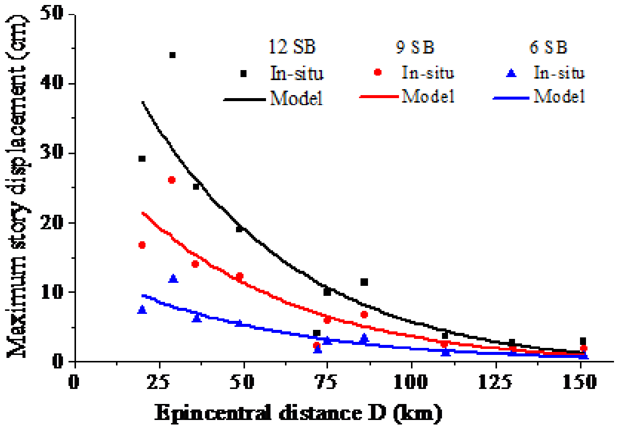
In seismic analysis, the fundamental period is the footprint of the structure, it allows calculating the base shear force in the equivalent static method [17], and enabling to get the spectral response of any structure by simply reading on the regulatory response spectrum, through the introduction of the fundamental period and the damping value [11]-[15].

For buildings considered in this study, the first two modes are modes of translation; the third one is torsion mode for all the considered buildings. The fundamental periods are in the range between 0.66 and 0.81 s for buildings 6 stories, between 1.07 and 1.29 s for buildings of 9 stories and between 1.20 and 1.60 s for 12 stories buildings. The number of modes considered for the buildings of six and nine levels is of 12 and it is 24 for the twelve-story buildings, ensuring that the participation factor for these modes is greater than 90%. The fundamental periods are more important for high buildings and decreases for less high buildings [11]-[14].

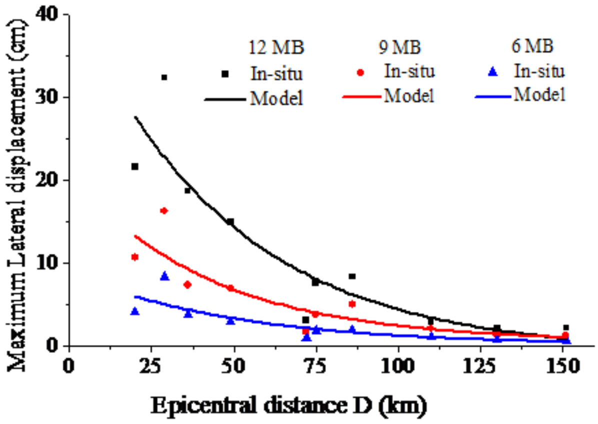
$$T_1 = \frac{2\pi}{\omega_1} \quad (1)$$

$$\omega_1 = \sqrt{\frac{M_1}{K_1}} \quad (2)$$

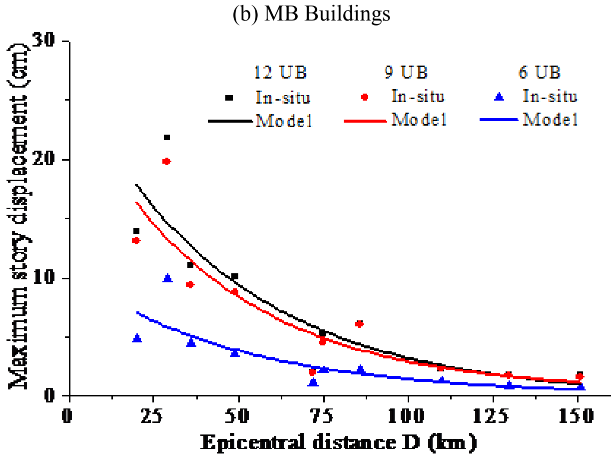
According to (1) and (2), fundamental period is intrinsic characteristic which depends on weight and stiffness. So, when the weight increases the fundamental period increases, that's why tall buildings (more stories) have fundamental periods more important than short ones. In the other hand, stiffness decreases the natural period, so, flexible building involves large natural period and are subject to large lateral displacements [11].



(a) SB Buildings



(b) MB Buildings



(c) UB Buildings

Fig. 3 Interstory drift versus epicentral distance and number of stories fitted by (3)

B. Lateral Displacement

On Fig. 3 are shown the maximal values of story displacement for the considered buildings for at various epicentral distances.

The values of this response evolve with the building height and take their maximum at the top of the whole studied buildings. This is explained by the fact that when the number of levels increases the weight increases which results in greater force that generates large displacement.

In the other hand the story displacement decreases with the increase of the epicentral distance. So the lateral displacement is directly proportional the building height and fundamental period.

One can note that around D = 29 km and 86 km, the lateral displacement values are more important than for buildings located closer to the epicenter [11]-[14]. This is explained by a local site effect [9].

The (3) gives the diaphragm displacement variation with respect to the epicentral distance and the fundamental period.

$$U = \frac{6.56}{1-0.537T} e^{-0.019D} \quad (3)$$

In order to reduce the negative effects of this lateral displacement, joints between adjacent structures should be more important than the maximum displacements of the buildings. The Algerian seismic code RPA99/ 2003 version, gives this equation to determinate the seismic joints width:

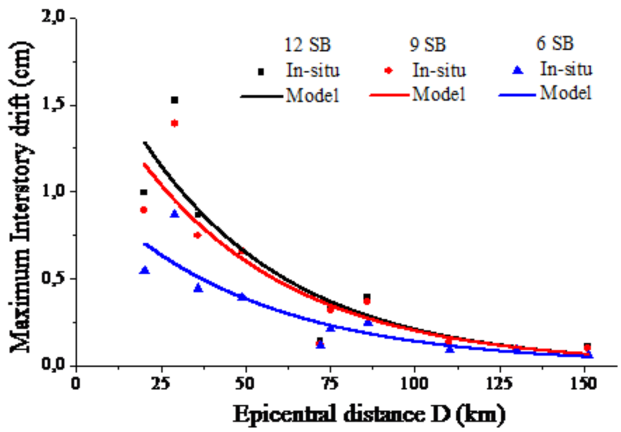
$$d_{min} = 15mm + (\delta_1 + \delta_2) \geq 40\ mm \quad (4)$$

where δ_1 and δ_2 are the maximum displacement value for each building.

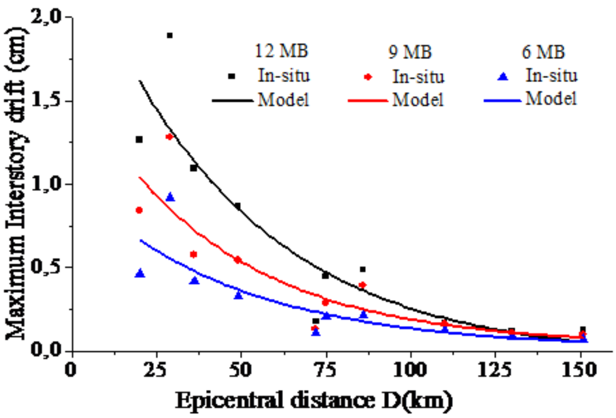
C. Interstorey Drift

This section deals with the interstorey drift which is the relative displacement between two adjacent floors.

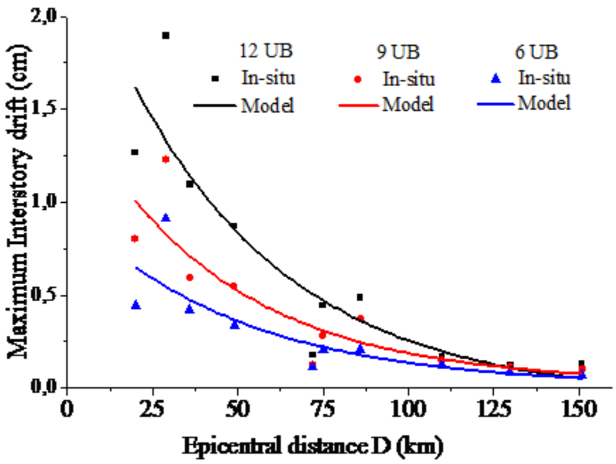
Fig. 4 gives the interstory drift for the different buildings.



(a) SB Building



(b) MB Buildings



(c) UB buildings

Fig. 4 Interstory drift versus epicentral distance and number of stories fitted by (5)

The interstory drift increases with the fundamental period, the building height and decreases when epicentral distances increases.

The same remark made for the lateral displacement around D = 29 km and 86 km, applies here.

It gives the diaphragm displacement variation according to the epicentral distance and the fundamental period (5).

$$\Delta U = \frac{0.55}{1-0.44T} e^{-0.019D} \quad (5)$$

Wide values of this response can damage the building or may even lead to partial or total collapse of the building, by threaten the nonstructural elements. For these different reasons, worldwide seismic building codes recommend a limitation of the interstory drift. Algerian seismic code limits it to 1.0% of the storey height

D. Condition of Site

For a given earthquake, the seismic force generally decreases when it moves away from the epicenter (increasing in epicentral distance). But local site nature and topography are also known to modify observed surface ground motions in several ways [18], and consequently the damages.

For example, buildings on ridges or peaks generally undergo seismic motions considerably amplified.

During the earthquake of Lambesc (Provence), France, in 1909, the village of Vernègues, built on a hilltop, was completely destroyed while the Vernègues neighborhood composed of the same kind of buildings, undergone less important damages. At Rognes, the houses on the top are those that have the most damage: indeed, the seismic waves reflected back inside the reliefs (slopes, ridges, peaks) remain concentrated as the energy they carry.

The amplitude of shaking peaks and ridges is greater than flat ground. The amplification is maximum for wavelengths comparable to the width of the relief. The opposite effect is observed: there are désamplification (mitigation) of the oscillations in areas with concave topography. Another case of site effect, sedimentary basins which amplify the waves and cause local damage greater than that estimated from the distance to epicenter (epicentral distance).

The most famous examples of these sites are the effects of the earthquake in Mexico in 1985 and, more recently, the Kobe earthquake in Japan in 1995.

In Mexico, the focus of the earthquake was located more than 200km from Mexico City who was however almost completely destroyed and where there were more than 35,000 dead. This city is located in a sedimentary basin which came into resonance, amplifying the seismic waves and disasters.

In Japan, while the seismic codes are the strictest in the world, the Kobe earthquake caused a lot of damage related to this same phenomenon of wave amplification in the Bay of Kobe.

For the herein study, the buildings located at 29 and 86km from the epicenter have undergone more seismic force than those located closest to the epicenter, this is explained by the amplification phenomenon due to the site effect [9] related to the resonance phenomenon due to variability of the bedrock depth for fundamental periods and an extension of the frequency content [2].

Finally, we can conclude that the building responses in term of displacements (lateral displacement and interstory drift) evolve in the same way as the building height, fundamental period and conversely to the epicentral distance -outside the local site effects- , they can be expressed by (3), (5), for the considered periods and epicentral distance ranges.

V. Conclusion

Earthquakes generate waves that can be slow and long, or short and abrupt. The length of a cycle in seconds is the period of the wave and is the inverse of the frequency. Each building has its fundamental period at which it vibrates if it is shaken by a shock.

The period (or frequency) is a primary key for the seismic design. If the period of the shock wave and the fundamental period of the building coincide, then the building "resonates" and its vibration will increase or "amplifies" several times.

When the ground shakes, buildings respond to accelerations transmitted through the ground with the building foundation. The inertia of the building (to remain at rest) can cause shearing of the structure which can concentrate stress on the elements of the structure resulting in failure or may collapses totally.

Tall buildings tend to amplify the movement of long period more than less tall one.

The engineer must be careful to ground the location of the considered building. Tall buildings should not be built on soft soil, but if it cannot be avoided, the building design should be revised in order to achieve a fundamental period far from the soil one.

Building height also affects in its turn the both displacements (lateral displacement and interstory drift) which reach the maximum values for the tallest buildings and decreases for lower buildings, therefore building displacements evolve with the building height, so directly proportional to the building natural period, which is explained by the fact that when the height increases (number of stories), weight increases and therefore earthquake force increases and then building responses increase. So the building displacements are changing in the same way as building height and fundamental period.

On the other hand, over the time, earthquakes have taught that outside of the resonance phenomenon, other site conditions have significant effects on the building seismic response through two capitals parameters: epicentral distance and soil nature.

Generally, all studies led this way, including this one, have shown that the increase in epicentral distance leads to the attenuation of the seismic wave which reduces the seismic force the structures undergone, in addition, the topography and the soil nature can amplify or mitigate these effects, these two factors due to the impact site have been the subject of many studies in order to reduce their impact on civil engineering structures.

The mitigating of seismic forces (response) due to the increase of epicentral distance is confirmed by this study, however, one should also highlight the presence of local site effect which was amplified around 29 and 86km from the epicenter where it was recorded respectively 0.52g and 0.16g.

All this, allows us to conclude that the building seismic responses are directly proportional to its height, its fundamental period, ground acceleration and inversely to the site epicentral distance,-outside the local site effect-.

REFERENCES

[1] M. Badaoui, «Influence de l'hétérogénéité géologique et mécanique sur le comportement des sols multicouches », Thèse de Doctorat, E.N.P, Alger, Algérie, 2008.

[2] Badaoui M., Berrah M. K., Mébarki A., "Depth to bedrock randomness effect on the design spectra in the city of Algiers (Algeria)". *Engineering Structures*, 2009.

[3] G. R. Searer and S. A. Freeman, "Design drift requirements for long-period structures". 13th world conference on Earthquake Engineering Vancouver, B. C., Canada August 1-6, 2004 Paper No. 3292.

[4] A. Rahman, A. A. Masrur Ahmed and M. R. Mamun, "Drift analysis due to earthquake load on tall structures ". Journal of Civil Engineering and Construction Technology Vol. 4(5), pp. 154-158, May 2012.

[5] M. Mahmoudi, "Determining the Maximum Lateral Displacement Due to Sever Earthquakes without Using Nonlinear Analysis". World Academy of Science, Engineering and Technology 50 2009:

[6] M. R. Lindeburg and K.M. MacMullin, "Seismic Design of Building Structures: A Professional's Introduction to Earthquake forces and design details". PPI (Professional Publications, Inc.), 11th edition (SEIS11P), 2014

[7] Anderson H, Jackson J. (1988). Active tectonics of the Adriatic region. Geophysics Journal Royal Astronomic Society 91 937-983.

[8] N. Laouami, A. Slimani 2008. Near field experimental seismic response spectrum analysis and comparison with Algerian regulatory design spectrum. The 14th World Conference on Earthquake Engineering October 12-17, 2008, Beijing, China

[9] N. Laouami, et al, 2006. Evidence for fault-related directionality and localized site effects from strong motion recordings of the 2003 Boumerdes (Algeria) earthquake: Consequences on damage distribution and the Algerian seismic code. Soil Dynamics and Earthquake Engineering 26 (2006) 991–1003.

[10] A. K. Yelles-Chaouche, H. Djellit and M. Hamdache, "The Boumerdes - Algiers (Algeria) Earthquake of May 21st, 2003 (Mw=6.8) CRAAG, Euro-Méditerranéen European-Mediterranean Seismological Centre www.emsc-csem.org. Newslatter N°20 septembre 2003.

[11] S. Dorbani, "Etude déterministe et analyse probabiliste des réponses de structures en BA à un séisme donné». Thèse de doctorat, USTHB, FGC, Alger, Algérie (2014).

[12] S. Dorbani; M, Badaoui; D. Benouar, "Structural seismic response versus epicentral distance and natural period: the case study of Boumerdes (Algeria) 2003 earthquake". Structural Engineering and Mechanics, Vol. 48, Nº 3, (2013).

[13] S. Dorbani; M, Badaoui; D. Benouar, "Influence of building design and site conditions on the structural response Boumerdes earthquake -2003-Algeria-data"; International Conference on vulnerability of Hazard, Risk and Disaster management (VAR 2011), 6th- 7th December, USTHB Algiers, Algeria (2011a).

[14] S. Dorbani; M, Badaoui; D. Benouar, "Influence of the height of the building and its fundamental period on seismic response Boumerdes earthquake-2003-Algeria-data", 8th International Seminar Lafarge, 13th-14th December, Algiers, Algeria, (2011b).CGS. (1999). *Règles Parasismiques Algériennes*. National Center of Applied Research in Earthquake Engineering, Algeria.

[15] ETABS (2005) Integrated Building Design Software. Computers and Structures, Inc. Berkeley, California, USA.

[16] Mehanny, S. S. F., (2012), "Are theoretically calculated periods of vibration for skeletal structures error-free?" Earthquakes and Structures. Vol. 3, N°1: 17-35.

[17] Stephen Hartzell, Mark Meremonte, Leonardo Ramírez-Guzmán, and Daniel McNamara, "Ground Motion in the Presence of Complex Topography: Earthquake and Ambient Noise Sources". Bulletin of the Seismological Society of America, Vol. 104, No. 1, pp. –, February 2014, doi: 10.1785/0120130088.

[18] Pan American Health Organization (PAHO).(2000), "Principles of disaster mitigation in health facilities", PAHO, Washington, D.C.