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# Structural seismic response versus epicentral distance and natural period: the case study of Boumerdes (Algeria) 2003 earthquake

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**Abstract.** This paper deals with the development of expressions relating structural seismic response parameters to the epicentral distances of an earthquake and the natural period of several reinforced concrete buildings (6, 9 and 12 storey), with three floor plans: symmetric, monosymmetric, and unsymmetric. These structures are subjected to seismic spectrum of accelerations collected during the Boumerdes earthquake (Algeria, May 21st, 2003, $Mw$=6.8) at different epicentral distances. The objective of this study is to develop relations between structural responses namely: base shear, storey displacements, interstory drifts and epicentral distance and fundamental period for a given earthquake. The seismic response of the buildings is carried out in both longitudinal transverse and directions by the response spectrum method (modal spectral approach).

**Keywords:** structural seismic response; epicentral distance; earthquake; reinforced concrete buildings; storey displacement

## 1. Introduction

Many researchers (Anderson and Jackson 1987, CRAAG 1994, Peláez *et al*. 2004, Pelaez and Hamdache 2004, Peláez *et al*. 2006, Laouami and Slimani 2008) consider that northern Algeria is an area of high seismicity, as well demonstrated by the seismic history of the region**.** During the past three decades, northern Algeria has unfortunately been hit repeatedly by destructive earthquakes, which have caused serious human and material losses. Those damages are either due to the earthquake itself or to secondary effects accompanying it, as Tsunami (Yelles *et al*. 2009, Ambraseys 1982, Perrey and Hebert 2008), site effect, liquefaction…etc. Apart from the effects of local phenomena (site effect), the structure's behaviour during an earthquake is directly related to several parameters. For this purpose, various reinforced concrete buildings (6, 9 and 12 stories) with different floor plans: Symmetrical, Mono-symmetrical and unsymmetrical are studied like those processed by (Dorbani *et al.* 2011a, b, Doğangün and Livaoğlu 2006, Badaoui 2008,

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Badaoui *et al.* 2009)**.** These structures are subjected to seismic accelerations recorded during the Boumerdes earthquake (Mw 6.8) of May, 21st 2003, (Ayadi *et al*. 2003, Hamdache *et al*. 2004, Yelles *et al*. 2004), whose effect was felt more than 150 km away.

The seismic responses of the buildings are analysed in both longitudinal and transverse directions by the response spectrum method (modal spectral approach).

## 2. Structural data

The modelled buildings are reinforced concrete of various heights (6, 9 and 12 stories) with three different floors geometry: symmetrical (SB), Mono symmetrical (MB) and unsymmetrical (UB)). Nine building types are considered and noted: 6-SB, 06-MB, 6-UB, 9-SB, 9-MB, 9-UB, 12-SB, 12-MB, 12-UB. The dimensions of the standard plan buildings are 22.7 × 13.75 m², with a story height of 3m.

The structural systems adopted are frames and shear walls in both directions. The columns, beams, slabs and shear walls are designed according to the requirements given in the Algerian earthquake regulations RPA 99 / 2003 version (CGS 2003)**.** The cross sections of the columns have been changed after the 3rd story for the 6th story buildings, and changed after the 4th for the buildings with 9 and 12 stories, with a further change of dimensions beyond the 8th story for 12 story buildings. The dimensions of the structural elements in both directions $x$ and $y$ are given in Table 1.

Most of building codes, adopted a practical concept to determine the inelastic design spectrum by dividing the elastic response spectrum by a factor. For the RPA99/2003 version, UBC 97 and IBC 2003, the factor used to reduce the elastic response spectrum is called the coefficient of structure performance (R), while for the EC8 is the behaviour factor (q), its value is based on the bracing system of the structure.

For the considered buildings, the bracing is ensured by frames with shear walls in both directions, in this case the RPA99/2003 recommends the value of 5 for the coefficient $R$.

### *2.1 Theoretical method*

The equation of the structure motion in the time domain can be expressed as

$$\mathbf{M\ddot{U}} + \mathbf{C\dot{U}} + \mathbf{KU} = \mathbf{F(t)} \tag{1}$$

Where, **M** is the mass matrix of the structure, **K** is its stiffness matrix, **C** is the viscous damping in the structure, $\mathbf{U}$, $\mathbf{\dot{U}}$, and $\mathbf{\ddot{U}}$ are respectively: the displacement, velocity and acceleration vectors, and $\mathbf{F(t)}$ is the applied force vector.

In order to evaluate the structures responses, civil engineers used to employ the regular design spectrum, or in some special cases: the time history records or the attenuation model.

To deal with the effect of the fundamental (natural) period of the structures and epicentral distance, on the maximum structural responses, one uses the response spectrum method (Modal Spectral Method) to determine the structural response to accelerograms recorded during the Boumerdes, Algeria earthquake (Mw 6.8) of May, 21st 2003, along each of the longitudinal and transverse directions.

## 3. Modelling and analysis of the results

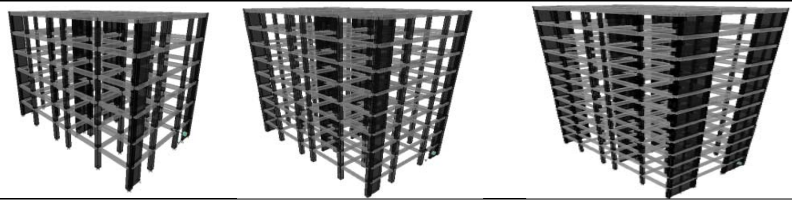
### *3.1 Modelling*

Using the software ETABS 9.5 (Computers and Structures Inc. 2008), to assess the structural response of buildings, a seismic linear analysis is performed by the spectral response method (spectral modal approach). By this method, it is searched for each mode of vibration, the maximum effects on the structure generated by the seismic forces represented by a response spectrum calculation. These effects are then combined to obtain the response of the structure.

This analysis is done separately in the longitudinal and transverse direction; In a first step, the longitudinal direction of the building is subjected to the E-W acceleration and the transverse one to the N-S, while in the second time, the first direction is subjected to the N-S acceleration and the second direction to the E-W. However, only the maximum response's values are presented.

The Table 2 summarizes the recorded peak ground accelerations, velocities, and displacements of the Boumerdes earthquake at the 10 considered stations. One notes that the E-W component is higher than the N-S one. This observation suggests a directional effect related to the fault orientation (Laouami *et al.* 2006).

Table 1 Dimensions of structural elements for the various buildings considered (cm)



| | | 6 Stories | | | | 9 Stories | | | | 12 Stories | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Buildings | Structural | 1-3 Stories | | 4-6 Stories | | 1-3 Stories | | 4-9 Stories | | 1-4 Stories | | 5-8 Stories | | 9-12 Stories | |
| | Elements | *bx* | *by* | *bx* | *by* | *bx* | *by* | *bx* | *by* | *bx* | *by* | *bx* | *by* | *bx* | *by* |
| Columns | C1 | 50 | 50 | 50 | 40 | 50 | 50 | 40 | 40 | 50 | 50 | 40 | 40 | 30 | 30 |
| | C2 | 60 | 60 | 50 | 50 | 60 | 60 | 50 | 50 | 70 | 70 | 50 | 50 | 40 | 40 |
| Beams | P | 25 × 50 | | | | 25 × 50 | | | | 30 × 60 | | | | | |
| Slabs | D | 15 | | | | 15 | | | | 15 | | | | | |
| Symetric | W1 | 25 | 175 | 25 | 175 | 25 | 175 | 25 | 175 | 30 | 430 | 30 | 430 | 30 | 30 |
| | W2 | - | - | - | - | - | - | - | - | - | - | - | - | - | - |
| | W3 | 25 | 75 | 25 | 175 | 25 | 175 | 25 | 175 | 30 | 430 | 30 | 430 | 30 | 430 |
| | W4 | - | - | - | - | - | - | - | - | - | - | - | - | - | - |
| Mono-symetric | W1 | 175 | 25 | 175 | 25 | 175 | 25 | 175 | 25 | 480 | 30 | 480 | 30 | 480 | 30 |
| | W2 | - | - | - | - | - | - | - | - | - | - | - | - | - | - |
| | W3 | 300 | 25 | 300 | 25 | 300 | 25 | 300 | 25 | 300 | 30 | 300 | 30 | 300 | 30 |
| | W4 | 25 | 75 | 25 | 75 | 25 | 175 | 25 | 175 | 30 | 30 | 30 | 30 | 30 | 430 |
| Un-symetric | W1 | 25 | 175 | 25 | 175 | 25 | 175 | 25 | 175 | 30 | 430 | 30 | 30 | 30 | 430 |
| | W2 | 300 | 25 | 300 | 25 | 300 | 25 | 300 | 25 | 480 | 30 | 480 | 30 | 480 | 30 |
| | W3 | 300 | 25 | 300 | 25 | 300 | 25 | 300 | 25 | 300 | 25 | 300 | 30 | 300 | 30 |
| | W4 | 25 | 175 | 25 | 175 | 25 | 175 | 25 | 175 | 30 | 430 | 30 | 430 | 30 | 430 |

Table 2 Recorded peak ground accelerations, velocities, and displacements of the Boumerdes earthquake (Laouami *et al.* 2006)

| | | E-W | | | N-S | | | Vertical (g) | | |
|---|---|---|---|---|---|---|---|---|---|---|
| D(km) | Type of station | A (g) | V(cm/s) | Displ (cm) | A (g) | V(cm/s) | Displ (cm) | A (g) | V(cm/s) | Displ (cm) |
| 20 | ETNA | 0.34 | 18.9 | 4.6 | 0.26 | 12.7 | 5.4 | 0.25 | 15.8 | 7.7 |
| 29 | SMA | 0.52 | 27.5 | 9.1 | 0.46 | 40.6 | 16.8 | 0.16 | 10.7 | 4.4 |
| 36 | SMA | 0.27 | 16.5 | 3.9 | 0.23 | 9.1 | 2.7 | 0.09 | 7.7 | 1.8 |
| 49 | SMA | 0,2 | 9.0 | 2.0 | 0.19 | 7.0 | 1.2 | 0.09 | 6.4 | 0.9 |
| 72 | SSA | 0.05 | 3.4 | 1.0 | 0.04 | 3.5 | 0.9 | 0.03 | 1.3 | 0.5 |
| 75 | SMA | 0.12 | 14.1 | 4.0 | 0.09 | 12.0 | 2.9 | 0.05 | 8.5 | 4.7 |
| 86 | SSA | 0.16 | 5.0 | 0.4 | 0.09 | 5.4 | 0.3 | 0.03 | 1.2 | 0.1 |
| 110 | SMA | 0.1 | 10.2 | 1.3 | 0.07 | 7.1 | 1.6 | 0.06 | 4.8 | 0.7 |
| 130 | ETNA | 0.03 | 2.3 | 1.4 | 0.026 | 1.9 | 0.6 | 0.016 | 1.6 | 1.5 |
| 151 | ETNA | 0.03 | 1.6 | 0.9 | 0.02 | 1.2 | 0.7 | 0.01 | 1.3 | 1.2 |

The radiation effect has not been considered directly in the herein study, but it was accounted through the value of the different records and consequently the response spectra.

The structure is fixed at the base, while the other nodes are free. Therefore, the finite element model does not consider the soil-structure interaction. The columns and beams are modelled by frame elements, while the shear walls are modelled by shell elements. Finally, the slabs are considered as rigid diaphragms in each level. In this analysis, the Young's modulus and density of concrete are respectively 28000 MPa and 25 kN/m$^3$. The damping value is 5% for all modes. The parameters of the dynamic response of structures involved in this study are:

- Base shear forces;
- Interstorey drifts;
- Lateral displacements;

### 3.2 Results

#### 3.2.1 Natural periods of the buildings

The number of modes considered for six and nine story-building is 12, and 24 for the twelve story buildings, for all considered cases, the corresponding participation factor exceeds 90% as required by the earthquake regulations. The fundamental period of the structure corresponds to the first mode and is related to the first pulse $\boldsymbol{\omega_1}$ by the following expression

$$\boldsymbol{T_1} = \frac{\mathbf{2\pi}}{\boldsymbol{\omega_1}} \tag{2}$$

The first nine modes, periods and the corresponding participation factors are presented in tables 3, 4 and 5. For the 6 story buildings, the fundamental periods are in a range between 0.66 and 0.81 s, between 1.07 and 1.29 for the 9 story-buildings and between 1.21 and 1.6 s for the 12 story buildings. The first modes for cases 6-MB, 6-UB, -9-MB, 9-UB, 12-MB and 12-UB vibrate mainly in the transverse direction, whereas cases 6-SB 9-SB and 12-SB vibrate in the longitudinal one. The third mode is a torsional mode for all considered buildings.

Table 3 First nine periods and modal properties for the six story-buildings considered

| | SB | | | | MB | | | | UB | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | Period (s) | Participation factor (%) | | | Period (s) | Participation factor (%) | | | Period (s) | Participation factor (%) | | |
| | | X | Y | Torsion | | X | Y | Torsion | | X | Y | Torsion |
| **1** | 0.81 | 78.2 | - | - | 0.66 | - | 65.5 | - | 0.67 | - | 70.3 | - |
| **2** | 0.55 | - | 70.5 | - | 0.43 | 70 | - | - | 0.52 | 45.5 | - | - |
| **3** | 0.48 | - | - | 72 | 0.42 | - | - | 62.1 | 0.44 | - | - | 45.6 |
| **4** | 0.27 | 12.3 | - | - | 0.21 | - | 11.2 | - | 0.19 | - | 14.1 | - |
| **5** | 0.15 | 4.3 | - | - | 0.11 | - | - | 14.3 | 0.13 | - | - | 9.6 |
| **6** | 0.14 | - | 17.5 | - | 0.11 | - | 5.1 | - | 0.11 | 12 | - | - |
| **7** | 0.13 | - | - | 16 | 0.11 | 18.9 | - | - | 0.09 | - | 5.8 | - |
| **8** | 0.10 | 2.7 | - | - | 0.07 | - | 2.4 | - | 0.06 | - | - | 3.7 |
| **9** | 0.07 | 1.3 | - | - | 0.05 | - | - | 5.3 | 0.05 | - | 3 | - |

Table 4 First nine periods and modal properties for the nine story-buildings considered

| | SB | | | | MB | | | | UB | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | Period (s) | Participation factor (%) | | | Period (s) | Participation factor (%) | | | Period (s) | Participation factor (%) | | |
| | | X | Y | Torsion | | X | Y | Torsion | | X | Y | Torsion |
| **1** | 1.29 | 77.1 | - | | 1.07 | - | 65.9 | - | 1.12 | - | 70.1 | - |
| **2** | 0.97 | - | 69.9 | | 0.76 | 69 | - | - | 0.91 | 52.5 | - | - |
| **3** | 0.82 | - | - | 71.3 | 0.71 | - | - | 62.7 | 0.77 | - | - | 52.8 |
| **4** | 0.42 | 11.9 | - | | 0.34 | - | 10.8 | - | 0.33 | - | 13.1 | - |
| **5** | 0.26 | - | 15.8 | | 0.20 | - | - | 13.1 | 0.24 | 7.8 | - | - |
| **6** | 0.24 | 4.5 | - | | 0.20 | 17 | - | - | 0.20 | 9.6 | - | - |
| **7** | 0.23 | - | - | 14.8 | 0.18 | - | 4.6 | - | 0.16 | - | 5.3 | - |
| **8** | 0.16 | 2.2 | - | | 0.12 | - | 2.1 | - | 0.11 | - | - | 3.8 |
| **9** | 0.12 | 1.4 | - | | 0.10 | - | - | 4.9 | 0.10 | - | 3 | - |

Table 5 First nine periods and modal properties for the twelve story-buildings considered

| | SB | | | | MB | | | | UB | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | Period (s) | Participation factor (%) | | | Period (s) | Participation factor (%) | | | Period (sec) | Participation factor (%) | | |
| | | X | Y | Torsion | | X | Y | Torsion | | X | Y | Torsion |
| **1** | 1.60 | 75.1 | - | - | 1.53 | - | 57.5 | - | 1.21 | - | 48.4 | - |
| **2** | 0.96 | - | 66.5 | - | 1.02 | 66.4 | - | - | 1.12 | 54.8 | - | - |
| **3** | 0.76 | - | - | 67.3 | 0.80 | - | - | 53.9 | 0.80 | - | - | 58.4 |
| **4** | 0.58 | 12.9 | - | - | 0.46 | - | 11.1 | - | 0.31 | 10.2 | - | - |
| **5** | 0.33 | 5.2 | - | - | 0.25 | 17.7 | - | - | 0.28 | - | 10.6 | - |
| **6** | 0.23 | 2 | - | - | 0.23 | - | 4.8 | - | 0.18 | - | - | 15.3 |
| **7** | 0.21 | - | 18 | - | 0.19 | - | - | 14 | 0.14 | 4.9 | - | - |
| **8** | 0.18 | - | - | 17.5 | 0.14 | - | 2.6 | - | 0.12 | - | 4.8 | - |
| **9** | 0.17 | 1.5 | - | - | 0.11 | 7.1 | - | - | 0.08 | 2 | - | - |

### 3.2.2 Base shear

The ground motions induce lateral forces at the base of the structure (base shear force). This force depends on several parameters: ground motion accelerations, structural weight and stiffness (fundamental period of vibration), soil conditions at the site and distance to the epicenter. The maximum base shear force for the various buildings is evaluated by using seismic response spectrums for the accelerograms recorded during the 2003 Boumerdes earthquake at different stations (Laouami *et al.* 2006), with a damping ratio of 5%. The base shear for the buildings at different distances from the epicenter is shown on the Fig. 1.

The maximum values obtained for the 12 story buildings and those of 9 and finally those of 6 stories. This is explained by the fact that when the number of stories increases, weight increases and consequently the base shear force increases. Furthermore, this force is as greater as the building is less symmetrical, because the eccentricity induces an additional shear force due to torsion, this induced force is of the same order in both longitudinal and transversal direction (Dorbani *et al* 2011a, b, Badaoui 2008, Badaoui *et al.* 2010). One notes that the shear force is directly proportional to building height and the fundamental period of the structures and inversely proportional to the epicentral distance.

It should be noted that around $D$ = 29 km and 86 km, the base shear values are more important than for buildings located closer to the epicenter. This is explained by a local site effect, which is confirmed by the high PGA values recorded at these stations (Table 2), located in the Mitidja quaternary basin where the soil is classified as soft compared to other stations within similar distances (Laouami *et al.* 2006).

For these figures, the expression of the base shear force with respect of the epicenter distance and the fundamental period can be expressed by the non linear exponential regression given by Eq. (3).

$$V = V_0 \, e^{R_0 D} \tag{3}$$

A: depending on the building fundamental period and given by the following non linear rational regression

$$V_0 = \frac{6.56}{1 - 0.44T} \tag{4}$$

The fit goodness statistics are given in the tables of the annexe A.

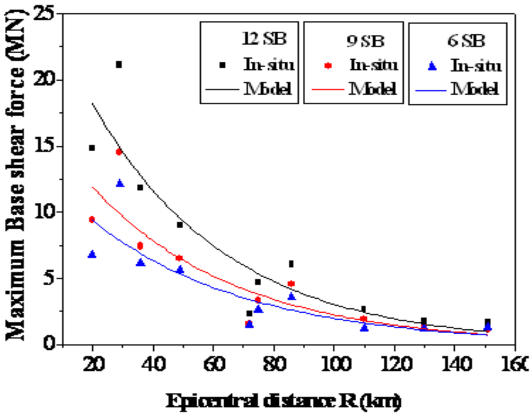
### 3.2.3 Interstory drifts

The relative displacement between two successive floors is called interstorey drift. Pan American Health Organization (PAHO 2000) assert that wide values of this interstory drifts can threaten the non structural elements and consequently damage the building or may even lead to partial or total collapse of the building, That’s why seismic building codes recommend that interstorey drifts should be limited. Algerian seismic code limits it to 1.0% of the storey height. The figure 2 gives the interstory drift for the different buildings. The interstory drift increases with the fundamental period, the building height and decreases when epicentral distances increases.

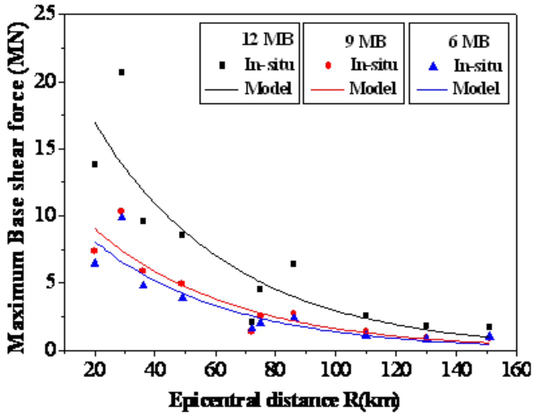
The same remark made for the base shear around $D$ = 29km and 86 km, applies here.

Using the nonlinear exponential regression, the variation of the interstory drift according to epicentral distance $D$ can be fitted by the following equation

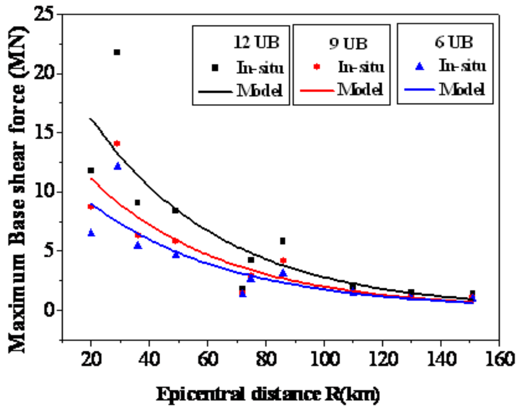
$$\Delta U = A \, e^{R_0 D} \tag{5}$$




(a) SB buildings

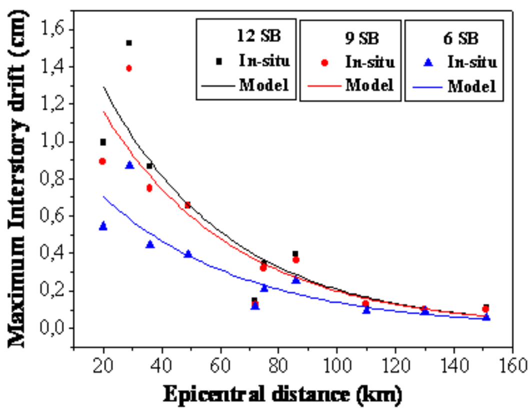



(b) MB buildings

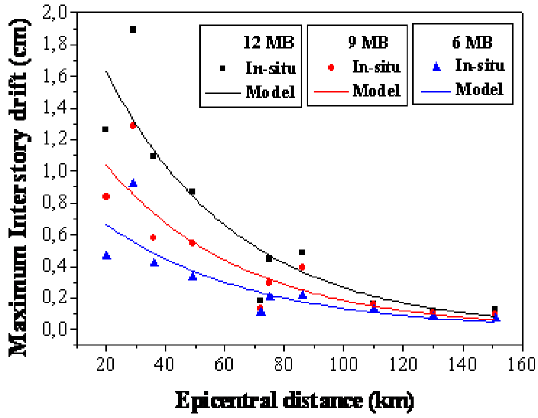



(c) UB buildings

Fig. 1 Base shear force versus epicentral distance and number of stories fitted by the Eq. (3)

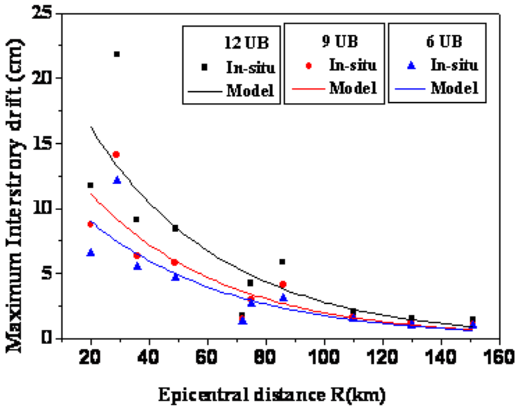



(a) SB buildings



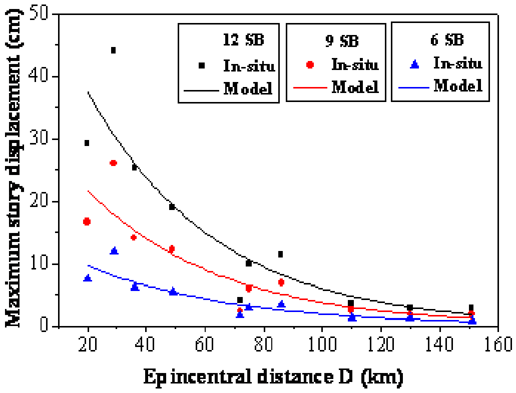

(b) MB buildings

Fig. 2 Interstory drift versus epicentral distance and number of stories fitted by the Eq. (5)

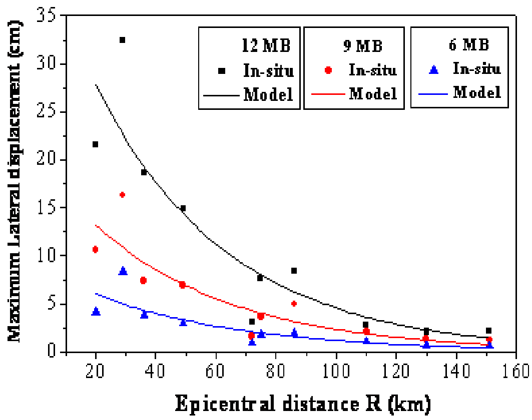



(c) UB buildings

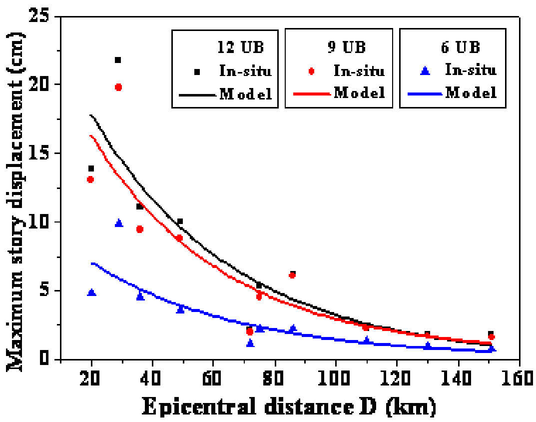
Fig. 2 Continued




(a) SB buildings




(b) MB buildings




(c) UB buildings

Fig. 3 Interstory drift versus epicentral distance and number of stories fitted by the Eq. (7)

A: depending on the building fundamental period and given by the following expression

$$A = \frac{0.55}{1 - 0.44T} \tag{6}$$

The error estimation of each coefficient is given in the tables of the annex B.

### *3.2.4 Lateral displacements*

This part deals with the lateral displacement for 6, 9 and 12 story buildings. The maximal values of story displacement for the different buildings for several epicentral distances are presented in Fig. 3.

The Eq. (7) gives the diaphragm displacement variation according to the epicentral distance and the fundamental period.

$$U = U_0 . e^{R_0 D} \tag{7}$$

A: depending on the building fundamental period and given by the following expression:

$$U_0 = \frac{6.69}{1 - 0.53T} \tag{8}$$

The tables in annex *C* give the error estimation of the coefficients in Eqs. (7) and (8).

Displacement in the longitudinal direction is always more important.

These values are more important near the epicenter and decrease when epicentral distances increase. As per base shear force and interstory drift, around *D*=29 km and 86 km, a local site effect emerged here, where it is found that the story displacement of the building situated at these epicentral distances is greater than those for building located closer to the epicenter.

As seen in Fig. 3, the diaphragm displacement of each story varies directly with the story's height, and takes its maximum value at the top for the whole buildings studied. As suggested by other authors (Badaoui 2008, Badaoui *et al*. 2009, Doğangün and Livaoğlu 2006) to reduce the negative effects of this lateral displacement, expansion joints between structures should be more important than the maximum displacements of the buildings.

The Algerian seismic code RPA99/Version 2003 gives this equation to determinate the seismic joints width

$$d_{min} = 15\text{mm} + (\delta_1 + \delta_2)\text{mm} \geq 40\text{ mm} \tag{9}$$

Where $\delta_1$ and $\delta_2$ are the maximum displacement value for each building calculated as follows

$$\delta_k = R\,\delta_{ek} \tag{10}$$

$\delta_{ek}$ : the displacement due to seismic forces $F_i$ (including the effect of torsion)
*R*: coefficient of structure performance.

### *3.2.5 Condition of site*

Local site conditions were considered by some researchers (Bard 1994, Safak 2001, Nour *et al*. 2003, Badaoui *et al*. 2009), because it can modify the seismic effect, and consequently the generated damages. Buildings on a hilltop, are generally seriously damaged while, the same kind of buildings, somewhere else, undergone less important damages, this is explained by the fact that buildings on ridges or peaks generally undergo seismic motions considerably amplified, indeed, the seismic waves reflected back inside the reliefs (slopes, ridges, peaks) remain concentrated. The amplification is maximum for wavelengths comparable to the width of the relief. The opposite effect is observed in areas with concave topography (Lay and Wallace 1995, Athanasopoulos *et al*. 1999).

Soil nature can modify the seismic effect, sedimentary basins amplify the waves and cause local damage greater than that estimated relied to the epicentral distance.

The attenuation of seismic consequent to the epicentral distance is found and confirmed by this study. Buildings located around 29 and 86 km from the epicenter have undergone more damage than those located around the epicenter. The increase of structure responses of these buildings can be related to the resonance phenomenon due to variability of the bedrock depth for fundamental periods and an extention of the frequency content (Badaoui *et al*. 2009).

The post-seismic observations reveal a NE–SW trend of the damaged area, corresponding to the maximum intensity area (Laouami *et al*. 2006). Furthermore, the main shock recorded accelerations during Boumerdes 2003 earthquake are higher on the E–W component than on the N–S one. These observations suggest a directional effect related to the fault orientation

Finally, we can conclude that the whole seismic responses studied evolve in the same way as the building height, fundamental period and inversely to the epicentral distance, outside the local site effects.

## 4. Conclusions

Behaviour of structures during an earthquake depends on several parameters: building conception, earthquake parameters as: PGA, response spectra, predominant periods, duration, nature and topography of the soil crossed by the seismic waves and finally epicentral distance.

In order to bring out the effect of the natural period and the epicentral distance on the structural responses, nine (09) reinforced concrete buildings references of 6, 9 and 12 stories according to their floor geometry: symmetric (SB), mono-symmetric (MB) and unsymmetric (UB) have been considered. The structural system of these buildings is a coupling between frames and shear walls in both directions.

An analysis under the effect of seismic response spectra of accelerograms recorded during the Boumerdes Algeria (May 21$^{st}$, 2003) earthquake, was performed using the software ETABS (Computers and Structures, Inc. 2008). The number of modes taken into account for buildings of six and nine stories is 12 modes and 24 for buildings of twelve floors. The fundamental periods for the considered buildings are in the range between 0.66 to 1.6 s (Tables 3-5). The first modes for cases 6-MB, 6-UB, 9-MB, 9-UB-12-MB, 12-UB and vibrate mainly in the y direction, while cases 6-SB, 09-SB and 12-SB vibrate in the direction x and the third mode is a torsional mode for all buildings considered. The fundamental periods of the buildings increases with its height, because the building mass increases and its stiffness decreases.

The base shear force reached the maximum values for the tallest buildings which means that it is directly proportional to the building height and then to its fundamental period. Base shear force takes its maximum value near the epicenter and decreases for large epicentral distances.

The interstory drifts reach their extreme values at intermediate stories; on the 4th storey for buildings with 6 and 9 stories, at 5th storey for 12-SB, 6th for 12-MB and 8th for 12-UB. It is more important for tall building and decreases with epicentral distance.

For the whole of the analyzed structures, the story height increases the diaphragm displacement which takes its maximum value at the top of the buildings. As a consequence, the seismic joints between structures should be more important than the maximum displacements of the buildings, as mentioned in the seismic codes. The diaphragm displacement is always more important near the epicenter and decreases for large epicentral distances.

In terms of epicentral distances, many authors have shown that the effect of an earthquake decreases or mitigates gradually with the growth of the epicentral distance (Ambraseys 1985, Ambraseys 1995, Arroucau *et al*. 2006, Boore *et al*. 1994, Peláez *et al*. 2003, Benouar 1994a, b). In addition, the underground topography and the soil nature can modify these effects; these two factors due to the site effect have been the subject of many studies in order to reduce their impact on civil engineering structures.

The local site effect emerged by this study at the two stations of Dar el Beida and El Afroun which are respectively at 29 km and 86 km from the epicenter, is also supported and confirmed by the high PGA values, recorded at these stations located in the Mitidja quaternary basin where the soil is classified as soft, compared to other stations within similar distances (Laouami *et al*. 2006). This is explained according to Badaoui *et al*. (2009) by the resonance phenomenon due to variability of the bedrock depth for fundamental periods and an extension of the frequency content.

The building seismic response is directly proportional to its fundamental period, ground acceleration and inversely to the site epicentral distance.

Through the herein study, formulas have been developed, for the following structural seismic responses: Base shear force, Story displacement and Interstory drift relating to the epicentral distance and the natural period.

The good fitting was verified according the statistics detailed in the annexes.

It is imperative to point out that, these formulations are valid in the range of periods and epicentral distances considered, it means: 1.6s for the natural period and 151 km for the epicentral distance.

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## Annexe A. Base shear force statistics

Table A.1 Values and standard error for SB buildings

| Building \ Equation | | $V = V_0 \cdot e^{R_0 D}$ Value | Standard Error |
|---|---|---|---|
| 12 SB | $V_0$ | 23.76 | 2.83 |
| | $R_0$ | -0.02 | 0.003 |
| 9 SB | $V_0$ | 14.55 | 1.87 |
| | $R_0$ | -0.02 | 0.003 |
| 6 SB | $V_0$ | 10.50 | 1.61 |
| | $R_0$ | -0.02 | 0.003 |

Table A.2 Values and standard error for MB buildings

| Building \ Equation | | $V = V_0 \cdot e^{R_0 D}$ Value | Standard Error |
|---|---|---|---|
| 12MB | $V_0$ | 21.3 | 2.62 |
| | $R_0$ | -0.02 | 0.003 |
| 9 MB | $V_0$ | 11.55 | 1.3 |
| | $R_0$ | -0.02 | 0.003 |
| 6 MB | $V_0$ | 9.78 | 0.77 |
| | $R_0$ | -0.02 | 0.002 |

Table A.3 Values and standard error for UB buildings

| Building \ Equation | | $V = V_0 \cdot e^{R_0 D}$ Value | Standard Error |
|---|---|---|---|
| 12 UB | $V_0$ | 18.4 | 2.6 |
| | $R_0$ | -0.02 | 0.003 |
| 9 UB | $V_0$ | 13.35 | 1.61 |
| | $R_0$ | -0.02 | 0.003 |
| 6 UB | $V_0$ | 9.75 | 1.2 |
| | $R_0$ | -0.02 | 0.003 |

Table A.4 Base shear fitting goodness statistics for the different considered building

| Building \ Equation | $V = V_0 \cdot e^{-0,02D}$ | | | | |
|---|---|---|---|---|---|
| | Adj. R-Square | R Value ( Correlation) | R-Square (COD) | Reduced Chi-Sqr | Root-MSE (SD) |
| 12 SB | 0.94 | 0.97 | 0.95 | 1.65 | 1.29 |
| 12 MB | 0.93 | 0.97 | 0.94 | 1.45 | 1.2042 |
| 12 UB | 0.91 | 0.96 | 0.92 | 1.57 | 1.25 |
| 9 SB | 0.92 | 0.97 | 0.93 | 0.86 | 0.93 |
| 9 MB | 0.94 | 0.97 | 0.95 | 0.40 | 0.63 |

Table A.4 Continued

| | | | | | |
|---|---|---|---|---|---|
| 9 UB | 0.93 | 0.97 | 0.94 | 0.60 | 0.78 |
| 6 SB | 0.87 | 0.94 | 0.89 | 0.80 | 0.89 |
| 6 MB | 0.97 | 0.97 | 0.97 | 0.14 | 0.38 |
| 6 UB | 0.91 | 0.96 | 0.93 | 0.42 | 0.65 |

Table A.5 Statistics and standard error for "A" fitting

| Equation / Statistics | $V_0 = \frac{a}{1 + b.T}$ | |
|---|---|---|
| Adj. R-Square | 0.91 | |
| R Value | 0.96 | |
| R-Square(COD) | 0.92 | |
| Reduced Chi-Sqr | 2.13 | |
| Root-MSE (SD) | 1.46 | |
| | Value | Standard Error |
| a | 6.56 | 0.53 |
| b | - 0.44 | 0.02 |

## Annexe B. Interstory drift statistics

Table B.1 Values and standard error for SB buildings

| Equation / Building | | $\Delta U = A . e^{R_0 D}$ | |
|---|---|---|---|
| | | Value | Standard Error |
| 12 SB | A | 1.55 | 0.13 |
| | $R_0$ | -0.02 | 0.002 |
| 9 SB | A | 1.36 | 0.12 |
| | $R_0$ | -0.02 | 0.002 |
| 6 SB | A | 0.80 | 0.05 |
| | $R_0$ | -0.02 | 0.002 |

Table B.2 Values and standard error for MB buildings

| Equation / Building | | $\Delta U = A . e^{R_0 D}$ | |
|---|---|---|---|
| | | Value | Standard Error |
| 12 MB | A | 1.97 | 0.16 |
| | $R_0$ | -0.02 | 0.002 |
| 9 MB | A | 1.2 | 0.06 |
| | $R_0$ | -0.02 | 0.001 |
| 6 MB | A | 0.66 | 0.03 |
| | $R_0$ | -0.015 | 0.001 |

Table B.3 Values and standard error for UB buildings

| Building \ Equation | | $\Delta U = A \cdot e^{R_0 D}$ Value | Standard Error |
|---|---|---|---|
| 12 UB | A | 1.05 | 0.07 |
| | $R_0$ | -0.02 | 0.002 |
| 9 UB | A | 1.15 | 0.06 |
| | $R_0$ | -0.02 | 0.001 |
| 6 UB | A | 0.64 | 0.04 |
| | $R_0$ | -0.014 | 0.001 |

Table B.4 Interstory drift fitting goodness statistics for the different considered building

| Building \ Equation | $\Delta U = A \cdot e^{-0.019D}$ | | | | |
|---|---|---|---|---|---|
| | Adj. R-Square | R Value ( Correlation) | R-Square (COD) | Reduced Chi-Sqr | Root-MSE (SD) |
| 12 SB | 0.97 | 0.99 | 0.98 | 0.004 | 0.06 |
| 12 MB | 0.97 | 0.99 | 0.98 | 0.007 | 0.08 |
| 12 UB | 0.98 | 0.99 | 0.98 | 0.002 | 0.04 |
| 9 SB | 0.97 | 0.99 | 0.97 | 0.004 | 0.06 |
| 9 MB | 0.99 | 0.99 | 0.99 | 0.001 | 0.03 |
| 9 UB | 0.98 | 0.99 | 0.99 | 0.001 | 0.03 |
| 6 SB | 0.98 | 0.99 | 0.98 | 8.15741E-4 | 0.03 |
| 6 MB | 0.98 | 0.99 | 0.99 | 4.41708E-4 | 0.02 |
| 6 UB | 0.97 | 0.99 | 0.98 | 7.22672E-4 | 0.03 |

Table B.5 Statistics and standard error for "A" fitting

| Statistics \ Equation | $A = \frac{a}{1 + b.T}$ | |
|---|---|---|
| Adj. R-Square | 0.79 | |
| R Value | 0.90 | |
| R-Square(COD) | 0.82 | |
| Reduced Chi-Sqr | 0.04 | |
| Root-MSE (SD) | 0.20 | |
| | Value | Standard Error |
| a | 0.55 | 0.07 |
| b | -0.44 | 0.04 |

## Annexe C. Lateral displacement statistics

Table C.1 Values and standard error for SB buildings

| Building \ Equation | | $U = U_0 \cdot e^{R_0 D}$ | |
|---|---|---|---|
| | | Value | Standard Error |
| 12 SB | $U_0$ | 45.65 | 3.61 |
| | $R_0$ | 0.02 | 0.002 |
| 9 SB | $U_0$ | 25.34 | 2.17 |
| | $R_0$ | 0.02 | 0.002 |
| 6 SB | $U_0$ | 10.91 | 0.70 |
| | $R_0$ | 0.02 | 0.002 |

Table C.2 Values and standard error for MB buildings

| Building \ Equation | | $U = U_0 \cdot e^{R_0 D}$ | |
|---|---|---|---|
| | | Value | Standard Error |
| 12 MB | $U_0$ | 33.66 | 2.80 |
| | $R_0$ | 0.02 | 0.002 |
| 9 MB | $U_0$ | 15.11 | 0.80 |
| | $R_0$ | 0.02 | 0.001 |
| 6 MB | $U_0$ | 5.86 | 0.31 |
| | $R_0$ | 0.02 | 0.001 |

Table C.3 Values and standard error for UB buildings

| Building \ Equation | | $U = U_0 \cdot e^{R_0 D}$ | |
|---|---|---|---|
| | | Value | Standard Error |
| 12 UB | $U_0$ | 20.41 | 1.40 |
| | $R_0$ | 0.02 | 0.002 |
| 9 UB | $U_0$ | 18.81 | 1.05 |
| | $R_0$ | 0.02 | 0.001 |
| 6 UB | $U_0$ | 6.84 | 0.41 |
| | $R_0$ | 0.014 | 0.001 |

Table C.4 Interstory drift fitting goodness statistics for the different considered building

| Building \ Equation | $U = U_0 \cdot e^{-0.019D}$ | | | | |
|---|---|---|---|---|---|
| | Adj. R-Square | R Value ( Correlation) | R-Square (COD) | Reduced Chi-Sqr | Root-MSE (SD) |
| 12 SB | 0.97 | 0.99 | 0.98 | 3.20 | 1.80 |
| 12 MB | 0.97 | 0.99 | 0.98 | 2.02 | 1.42 |
| 12 UB | 0.98 | 0.99 | 0.98 | 0.60 | 0.77 |
| 9 SB | 0.97 | 0.99 | 0.97 | 1.33 | 1.15 |
| 9 MB | 0.99 | 0.99 | 0.99 | 0.18 | 0.43 |

Table C.4 Continued

| | | | | | |
|---|---|---|---|---|---|
| 9 UB | 0.98 | 0.99 | 0.99 | 0.31 | 0.56 |
| 6 SB | 0.98 | 0.99 | 0.98 | 0.16 | 0.40 |
| 6 MB | 0.98 | 0.99 | 0.98 | 0.04 | 0.20 |
| 6 UB | 0.98 | 0.99 | 0.98 | 0.07 | 0.26 |

Table C.5 Statistics and standard error for "A" fitting

| Statistics \ Equation | $U_0 = \frac{a}{1+b.T}$ | |
|---|---|---|
| Adj. R-Square | 0.95 | |
| R Value | 0.98 | |
| R-Square(COD) | 0.95 | |
| Reduced Chi-Sqr | 8.94 | |
| Root-MSE (SD) | 2.99 | |
| | Value | Standard Error |
| a | 6.69 | 0.67 |
| b | -0.53 | 0.012 |