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# THE VERTICAL SEISMIC COMPONENT "THE COLUMBUS' EGG IN EARTHQUAKE ENGINEERING"

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## ABSTRACT

In the present communication it is tried to be demonstrated the catalytic importance of the vertical component of the shaking on the earthquake response of structures build in epicentral regions, either acting independently, or in combination with the other two horizontal components of the seismic motion. In the epicentral regions of the most of the damaging Greek earthquakes of the last decades there is strong evidence of the presence of the vertical seismic component. The paper refers to normal shallow earthquakes which are the majority of Greek and of many European earthquakes. For these earthquakes a model for the initial tectonic motion is proposed. The resulting motion on the surface of the ground is a superposition of the various well-known types of waves and of the response of the ground to an abrupt tectonic subsidence. Some constructional and design measures are proposed for a tentative protection of existing and new structures in order to confront the vertical component.

*KEYWORDS*: Normal faults, vertical component, epicentral regions, protective measures.

## INTRODUCTION

The title has a twofold meaning: first, due to the simplicity of the subject under consideration, and second, due to the similarity of the breaking of the egg on the table that Columbus made – according to the myth – with the impact and breaking of the structures on the ground or on their foundation body due to the vertical component of the shaking. The paper refers to epicentral regions of strong shallow earthquakes and especially to normal faults that occur in Greece and other European regions.

The aim of the paper is multiple:

a. To trigger the interest of the relevant scientists in order to direct their research towards this subject, both in the analytical and experimental domain.
b. To demonstrate that the vertical seismic component was the main damaging parameter in the various epicentral regions, as for example the Parnitha (1999) and other Greek strong

earthquakes as well as earthquakes in various regions around the world, where prevail similar seismotectonic conditions.

c. To collect as much as possible evidence from the field, after damaging events, that justify this point of view. Further, to be widely accepted that the vertical component is the dominating parameter in epicentral regions of shallow normal earthquakes and very important when it comes in combination with the horizontal motion in earthquakes due to strike – slip faults.
d. To be adequately designed and constructed the repair and strengthening of structures damaged in epicentral regions of this type of earthquakes.
e. To gather new knowledge that will enrich the new structural codes, in order to influence the way of designing and calculating of new structures, the way of carrying our experiments and the various procedures in seismic modeling and in analyzing the response of the ground for microzonation studies. To this goal the paper will contribute in designing the seismic passive or active control of structures to resists also the vertical motions that dominate in epicentral regions. It must be mentioned that the vertical component as it is dealt today in the various earthquake design codes is not satisfactorily covered.

## THE VERTICAL MOTION IN THE EPICENTRAL REGION

The structure is subject to the motion of its base, which in turn is composed of two motions, different in nature:

### *The vertical tectonic fall*

This motion is the result of the abrupt falling of the bedrock under the action of the constant acceleration of gravity (1.0 g) from A to B, see Figure 1 (the velocity in B is $u_B$). According to geodetic data, Kontoes et al [1] found that the tectonic vertical fall was from 0 to about 8 cm, during the Parnitha (1999) event.

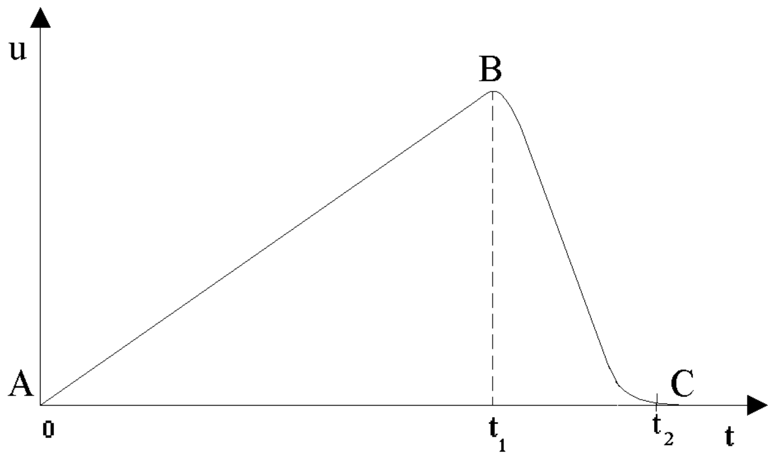


**Figure 1** The motion at the lower part of the bedrock formation

The time $t_l$ required for this free fall under the effect of 1.0 g acceleration of gravity is given in Eq. 1:

$$t_1 = \sqrt{2 \times S / a_g} \tag{1}$$

which for a = 9.81 ($m \times sec^{-2}$) and S = $8 \times 10^{-2}$(m) gives: $t_1 = \sqrt{2 \times 8 \times 10^{-2} / 9.81} = 0.128$ (sec).

It is worth to mention that the duration of the strong motion was no more than 3-4 (sec) in the epicentral area.

The velocity of the bedrock above the fault is given by the formula:

$$u_B = a_g \times t_1 = \sqrt{2 \times S \times a_g} \tag{2}$$

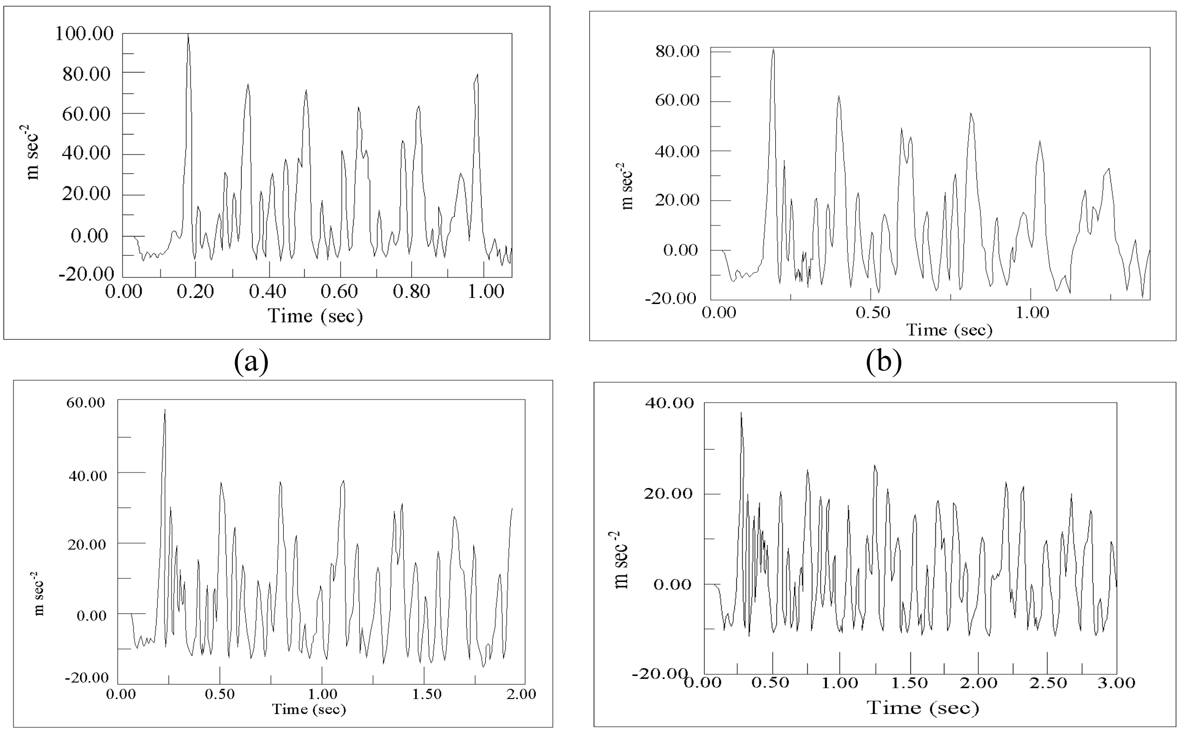
This, for the case under consideration gives: $u_B = 9.81 \times 0.128 = 1.256$ ($m \times sec^{-1}$)

At point B in Figure 1 the bedrock reaches its base, comes in collision with it and finally stops at point C. The time duration within which the impact phenomena are actually produced, is between time instances $t_1$ and $t_2$, and is given by Eq. (3).

$$\Delta t = t_2 - t_1 \tag{3}$$

The value of the velocity $u_B$ contributes to the final impact phenomena, but at a much lower scale, since its value is limited to an upper value resulting from the tectonic subsidence. This is a function of the magnitude of the earthquake.
The acceleration produced is given by Eq. (4).

$$a = \frac{\Delta u}{\Delta t} = \frac{u_B}{t_2 - t_1} \tag{4}$$



(a) (b)

(c) (d)

**Figure 2** Accelerations calculated at the surface of the soil deposit for shear wave velocity: deposit (a):$V_S$=450msec$^{-1}$,deposit (b):$V_S$=350msec$^{-1}$ , deposit (c): $V_S$=250msec$^{-1}$, deposit (d): $V_S$=150msec$^{-1}$

The sharpness of the curves of the velocity diagram in Figure 1 at points B and C as well as the time duration Δt of the collision show the type of the tectonic impact (sharp curves – more elastic and less plastic impact, smooth curves – less elastic and more plastic impact).

Therefore, the value of the created acceleration greatly depends on the characteristics mentioned just before and not so much on the value of $u_B$, namely the magnitude of the earthquake. In other words, this means, as it has already been observed, that earthquakes even of a rather small magnitude may produce high epicentral accelerations with damage potential.

Due to the tectonic motion A, B and C given in Figure 1, and according to the specific case of the soil characteristics that lays above the bedrock, one may define the motion at the surface of the ground. With the use of ABACUS code, four 30,0 (m) deep soil deposits with a variety of different $V_s$ = 450 ($m \times sec^{-1}$), 350 ($m \times sec^{-1}$), 250 ($m \times sec^{-1}$) and 150 ($m \times sec^{-1}$) – constant along their depth – were analyzed. The model does not accept tentional stresses. The accelerations at the surface were calculated. The resulted motions are given in Figures 2a, 2b, 2c and 2d respectively. The mass density was taken $\rho = 2$ Mg/m$^3$ and the Poisson ratio $v$=0.3. The shear modulus of the soil deposit was calculated according to the formula $G = V_s^2 \times \rho$. The value of the duration was taken equal to $\Delta t = 0.016$ (sec). From the response at the surface of the soil deposit one may observe that the diagrams are unsymmetrical along the zero line. The downwards motion is always with 1.0 g acceleration – free fall. The response at the surface is a strong non-symmetrical vertical P wave, with high frequency content.

*The wavy motion*
This motion is the result of the well-known P, S and Rayleigh waves that dominate at the epicentral region.

The final motion at the surface is the convolution of the two types of motions, due to the tectonic subsidence and due to the rest of the waves. As a direct result of this convolution, and not only to that, is the fact that the motion at the epicentral region is very variable from one site to the other – even within a distance of, say, 50-100 m – in amplitude and in phase.

## THE TREND OF THE MODERN SEISMIC CODES

Structures do not distinguish the type and source of the motion at their foundation ground. The only important parameter is the input motion along the three main coordinates of the structure (x, y, z) and their phase difference along each direction, due to the size of the structure.

It is a fact that a very important progress has been carried out in the domain of Earthquake Engineering, mainly with the installation of large number of strong motion instruments and the recording of the seismic motion at the field. The respective seismic analysis of structures at the present is almost absolutely based on the obtained records. In fact, as a contemporary engineer could say, the relevant knowledge came as a strong light into the scientific darkness that dominated the domain of Earthquake Engineering until few decades ago. This light was so strong that made faint the technical knowledge at this domain. It limited us so that to be satisfied with the recordings of the instruments. Enforced us not to proceed in very detailed evaluations of the real observations after destructive earthquakes. The importance is to analyze both the damaged and the non-damaged structures, which may be adjacent one to the other and even might be very similar, and the soil conditions are also similar.

Following this practice we do not consider of a paramount importance our obligation to get the clearest possible idea of the motion of the ground before drawing any conclusions about the response of the structure. On the other hand, the evaluation of the response of structures and mainly of the simplest ones may result in very important conclusions about the response of the ground. For example, the maximum gap between the frame and the brittle wall may give the displacement response spectrum value at the respective period of the frame.

It must be mentioned here that traditional analogue strong motion instruments do not record monotonic motions of the ground but only the resulting wavy motions. They record motions of low frequencies due to their low pass filters up to no more than 20-25 Hz. Now, with the use of more sophisticated digital strong motion instruments it is certain that very high acceleration will be registered.

As a logical result of all these is that during the recent years the design accelerations are continuously increased for civil engineering structures as well as for electromechanical installations. This may be called "instrumental" increase of the design accelerations and not natural, since earthquakes occurred, certainly, since the formation of the earth. According to various observations and analytical calculations, the maximum vertical accelerations at the epicentral regions are of the order of 1.0 g or much greater, and as already mentioned they are equally high almost independently of the magnitudes of the shallow shocks. With the lapse of time, higher accelerations will be recorded which refer to single point on the ground.

It has also been proved that the vertical accelerations are more quickly absorbed with the epicentral distance compared to the horizontal ones. This fact enhances what stated just above, that with the increase of the number and areal distribution of strong motion instruments the "instrumental" design accelerations will be increased in the coming years, and the vertical accelerations will be more drastically increased rather than the horizontal ones. The magnitude of the earthquake has a loose correlation mainly for the maximum accelerations of the vertical component in epicentral regions.

Therefore, with the lapse of the years a general opinion is formed that for the horizontal direction the seismic coefficients used in the past are inadequate and they are much smaller than what they should be. This opinion is supported besides the recordings by observational data also, on damages in structures after destructive earthquakes during the last decades. Following this logic one comes to the conclusion the design base accelerations should be increased as well as the required ductilities. The increase of these parameters is at such a level that a problem may appear as far as the possibility of the realization of structures with such characteristics is concerned. Perhaps the inclusion into the structures of various systems for passive or active control and damping mechanisms might be proved indispensable even for simple structures.

The trend for increasing the design ground motion seismic parameters should be hold back at a certain level, as far as the horizontal direction is concerned. This increase is unprofitable and without giving the desired protection compared to the required heavy economic investments and the resulted difficulties for good architectural solutions.

The most of the damages at epicentral regions, as already mentioned, should be rent to the presence of the vertical component (standing alone or in combination to the horizontal ones) and not due to inadequate horizontal seismic coefficients. Also, in epicentral regions a large number of damages are in new buildings. This is for regions where already high design ground accelerations are used. The existing earthquake resistance of structures designed according to the modern codes it must be considered as more than just adequate and very satisfactory, if only horizontal seismic component were dominating in epicentral regions of shallow earthquakes. But the resistance against the strong impulsive type of shocks is only partially achieved due to existing marginal safety factors and over design of the new structures.

## BASIC CHARACTERISTICS OF SEISMIC VIBRATION IN THE EPICENTRAL AREA

It has been observed that the characteristics of the seismic vibration differs greatly both in quality and in quantity between two points inside the epicentral area of shallow earthquakes.

These differences may occur even between two adjacent land pieces and distances as short as 50 to 100 m. For instance, there are cases of building collapse and at the same time, in the land nearby the signs of seismic motion are minor.

Therefore, the readings from the instruments on the site cannot be considered representative of the ground motion, neither of the maximum nor of the minimum of this motion. Hence, the instruments must be situated densely enough such as to make possible the recording of the seismic motion in the epicentral area. It is very difficult, if not impossible, to have instruments so densely installed in the epicentral areas since the later has a radius in the order of 10 km for common Greek shallow earthquakes. However, in cases where there are foreshocks the epicentral area of the main earthquake is more or less denoted.

A basic characteristic is that the absorbsion of the vibration and especially of the vertical one, along the distance, is much more pronounced compared to that derived from the well known equations which are based in the analysis of horizontal movements. These movements are beyond the epicentral area. Hence, by using the aforementioned equations there is little reliability in extrapolating the accelerations from outside the epicetral area in order to obtain the accelerations inside it. Data based on recordings of small scale aftershocks will hardly lead to any conclusions as of the intensity of the horizontal and vertical components of the main earthquake.

The frequencies of the vertical vibrations have a wide range beginning from values in excess of 10 Hz, depending on the quality of the ground. The vertical accelerations of the epicentral area in which this paper refers are significant and in excess of 1.0 g. In the downward movement of the ground the instrument, either alone or together with its base, will, as a result, detach or remain swinging for a (minimal) time period, until the gravity will cause them to drop on their base. It is well known that if the surfaces where the impact takes place are hard and of high strength (e.g. rock) the recorded accelerations will be much higher than those recorded if the impact surface was softer (reduced E) or of reduced strength (plastic impact).

Therefore, in this case, the readings we get from the accelerometers are significantly unsymmetrical: in one direction while the instrument swings above the ground it drops freely and records 1.0 g whereas, at the time of its impact on the ground the recorded accelerations varie depending on the type of the impact. In certain, few only cases these recordings may be of some importance for the design of structures. As it is well known, the dynamic magnification spectra based on impact are almost horizontal for structure periods between 0.5 $t_a$ and 2 $t_a$ where $t_a$ is the duration of the impact. This means that for the aforementioned periods the structures have the same coefficient of dynamic magnification (there are no resonance phenomena).

In relation to what was previously mentioned, of significant importance are the recordings of the reverse lateral earthquake Nahanni, Canada 1985, December 23 at 05:16 GMT, available from the Internet (Cosmos [3]). The significant asymmetry in the recordings of the vertical component is clearly seen, thus supporting what was mentioned before concerning the impact of the instrument or of its foot on the underlying base. These recordings are of great importance since the instruments which recorded the earthquake were digital with filters between 0.2 Hz and 62.5 Hz (compared to 20-25 Hz of the analogue accelerometers). As a result, these instruments can record high frequency impact vibrations, which concern mainly the vertical component. The depth of the focus of the main earthquake is 6 km and its magnitude ie $M_s$= 6.9 and three stations recorded the earthquake:

Station No 1 is situated in epicentral distance 6.0 km and recorded the following maximum values:
Component $10^o$, PGA: 956.7 (cm/s/s)

Component Up, PGA: 2322.4 (cm/s/s)
Component 280°, PGA: 1319.1 (cm/s/s)

Station No 2 is situated in epicentral distance 8.0 km and recorded the following maximum values:
Component 360°, PGA: 190.2 (cm/s/s)
Component Up, PGA: 386.5 (cm/s/s)
Component 270°, PGA: 534.4 (cm/s/s)

Station No 3 is situated in epicentral distance 16.0 km and recorded the following maximum values:
Component Up, PGA: 178.0 (cm/s/s)
Component 270°, PGA: 191.6 (cm/s/s)

The focus of the aftershock of December 25, 1985, 05:48 GMT is 10.0 km deep and its magnitude is $M_s = 5.4$. The recordings from station No 1 were:
Component 10°, PGA: 224.1 (cm/s/s)
Component Up, PGA: 110.1 (cm/s/s)
Component 280°, PGA: 87.7 (cm/s/s)

The ratios of the vertical acceleration to the mean value of the two horizontal for each station are given in Table 1 for the main shock.

**TABLE 1**

RATIOS $a_{vert} / a_{horiz}$ FOR THE MAIN SHOCK

| Station | No 1 (Δ=6.0 km) | No 2 (Δ=8.0 km) | No 3 (Δ=16.0 km) |
|---|---|---|---|
| $a_{horiz}$ (cm/s/s) | 1137.9 | 362.3 | 191.6 |
| $a_{vert}$ (cm/s/s) | 2322.4 | 386.5 | 178.0 |
| $a_{vert} / a_{horiz}$ | 2.04 | 1.07 | 0.93 |

Whereas, for the aftershock the ratio $a_{vert} / a_{horiz} = 110.1 / ((224.1 + 87.7)/2) = 0.70$.

From these relationships it is derived that the ratio of the vertical acceleration to the horizontal maximum acceleration is a function of the epicentral distance and the magnitude of the earthquake. This ratio varies from 2.04 to 0.93, whereas for the aftershock of magnitude M = 5.4 the ratio is 0.7. This value comes to an agreement with the codes about the relatio of the vertical to horizontal acceleration.

The ratios of the accelerations between the three stations are given in Table 2.

**TABLE 2**

ACCELERATION RATIOS BETWEEN STATIONS

| Station | No 2 / No 1 | No 3 / No 1 | No 3 / No 2 |
|---|---|---|---|
| Horizontal | 0.318 | 0.168 | 0.529 |
| Vertical | 0.166 | 0.077 | 0.460 |

It is clear that the reduction of the values of the vertical acceleration is much more significant compared to the reduction of the horizontal component.

By using the Donovan (1973) relation:

$$a = 1080\, e^{0.5M} (R + 25)^{-1.32} \tag{5}$$

the acceleration ratios between the three stations for hypocentral distances $R_1$=8.5 km, $R_2$=10 km and $R_3$=17.1 km respectively are: $a_2 / a_1 = 0.94$, $a_3 / a_1 = 0.74$, $a_3 / a_2 = 0.78$

These values differ greatly from the recordings of the earthquake under discussion. According to this spectrum of the vertical component, the values for periods less than 0.15 sec vary, depending on the damping, between 2.0 g and 6.0 g. It is clear that for the same periods and damping greater than 5% the spectrum is flat and its spectral magnification is small.

Because of the fact that the spectrum is flat in the epicentral area, the periods of the structures inside this area and all the relevant dynamic characteristics of the structures except damping are insignificant in the behavior of the structures as well as in the interpolation of the damages observed in the epicentral areas.

## THE PRINCIPLE OF THE ANALOGUE SEISMIC BEHAVIOUR OF STRUCTURES AND DAMPING

The fundamental requirements for a sound and safe earthquake response of a structure is, according to the Greek seismic code: (a) the avoidance of collapse (the probability of collapse to be very small) in despite of the intensity of the seismic motion and especially of how many times higher is the intensity compared to the design values; (b) the damages to be limited and repairable due to the design earthquake and (c) to be assured a minimum level of functions of the structure according to its use.

These requirements, nevertheless, cannot be met unless the deformational and loading state that is developed in its members during a real earthquake are analogous to the designed ones. This requires that the design and construction give almost constant ratios between the constructed seismic capacity and the resulted after an earthquake. And this must yield for all members (at least the important ones). In the usual earthquake designs, the member loads are null almost in the centers of beams and columns. If the loading is vertical the member forces will be maximum at this point.

In the laboratory it has been verified that when the structures are well designed and are loaded according to their design with consecutive input motions of increasing intensity, the structures really present a high seismic capacity. Values of overstrength like two or even three times the design accelerations are common for buildings and civil structures. Once the excitation and the response of the structure create member forces, which are not analogues to the design values, the structure easily may reach its ultimate state without having being exhausted its “ common seismic capacity”. And this is as it has been designed mainly against the horizontal component, according to the existing codes.

The available damping parameters in a bare structure might be inadequate unless special care has been taken. Due to the high frequency content and the impact type of the vertical seismic input motions the damping is very effective in reducing the consequences of this type of motion. Therefore, structures or structural members that provide damping are very profitable to be included in a structure. For example, see Benedetti and Carydis [2] for masonry structures that spent more than the 50% of their strength and stiffness in order to anticipate the vertical component. Also, the brick wall partitions in reinforced concrete framing structures must be considered as the basic mechanism to absorb seismic energy and most of the effects due to the vertical component.

## THE MECHANICAL PHENOMENA DUE TO THE VERTICAL COMPONENT

A summary of observations due to the vertical component is given below:

a. Structures are dislodged from their foundations, or toppled, without being damaged their framing system due to relative deformations between stories (distinguish from liquefaction).

b. Columns are broken in the form of an explosive manner either above their foundations or under the slab of the first storey. In many cases there are lighter damages in the columns at any distance from its base within the ground floor.
c. Beams and slabs penetrate the columns
d. Cantilevers fall dawn
e. Partial collapse of buildings. One part is standing and the other is on the ground. In most of the cases there are no partitions in the ground floor of the collapsed part in contrary to the standing one.
f. Doors, portraits, radiators and other appliances that are hanging from the walls are dismantled and fall dawn.
g. The collapsed buildings are almost within their foundation area and any remaining columns or walls are almost vertical.

For only qualitative purposes the axial specific shrink of the columns of a building is $\varepsilon=\Delta l/h$. Which for $\Delta l = 5cm$ and storey height $h=2.5m$ the resulted strain is of the order of $\varepsilon=2.0\%$ which is impossible to be undertaken elastically from a concrete or even from a steel columns. According to analytical procedures, it was found that when some discontinuity of the stiffness of a column exists, a concentration of axial deformations takes place and the failure is inevitable.

## PROPOSALS FOR DESIGN AND CONSTRUCTIONAL CONSIDERATIONS

The proposed measures in order to anticipate the vertical impact seismic component are the following.

a. Construction of the foundation body on a soft layer in order to absorb the shock.
b. Very good confinement of columns (with close stirraps) and column to beam joints with crossing beams on the joint.
c. Make a calculation in order to prove that the structure is safe with the multiplication of the vertical design loads of the columns at their lower stores with a coefficient of two.
d. Check analytically in order to prove that the structure is safe under creation of tensional forces in columns.
e. Check analytically that the safety of slabs and beams for about duplicating thir vertical loads.
f. Check for stiffer horizontal load bearing systems. Frequencies of more than 20 Hz should be achieved.
g. Provision of the necessary details in the joints, in order to anticipate an upwards motion of beams and slabs.
h. In existing structures non bearing partitions should be strengthened mainly at the ground floor.

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