# Code requirements in BIS design to withstand large accelerations and design spectral values

Antonello De Luca[a], Laura Giovanna Guidi[a], Giuseppe Brandonisio[a]
*Dipartimento di Strutture per l'Ingegneria e l'Architettura, Università degli Studi di Napoli Federico II, Piazzale Tecchio 80, Fuorigrotta, 80125 Napoli*

*Keywords: Earthquake response spectrum, spectral value, destructive earthquake, seismic design*

## ABSTRACT

In the history of earthquake engineering 1940 El Centro Earthquake represents a milestone: its maximum recorded peak ground acceleration of 0.35g, corresponding to a spectral acceleration of 0.90g, have influenced the definition of seismic design actions in all building codes, even today based on the probabilistic response spectrum approach. However, data from recent earthquakes have pointed out some "faults" in this procedure, introducing many questions about the achievement of actual seismic design methods. As argued in this paper, the analysis of spectral values from recent earthquakes underlines that seismic actions are really much higher than the ones defined according to codes. Therefore, an excursion among the worst earthquakes happened in the last 70 years is presented, valuing changes in terms of spectral acceleration, velocity and displacements. If Mexico City EQ (1985) showed a Sa(g)=0.66g corresponding to T=2.06s, nine years later during Northridge Eq. (1994) a spectral displacement $S_d$= 60.48cm was valued at T=2.58s. Later, Tohoku EQ (2011) recording PGA of 2.7g or the spectral displacement greater than 90cm during the Christchurch EQ (2011) has underlined the need to face earthquake spectral values not foreseeable previously. This results in the need for a more effective design procedure, a better quality in construction and a higher accuracy in details.

## 1 INTRODUCTION

The evaluation of the nature of structural damages caused by earthquakes is essential in improving seismic design criteria. Studies of the distribution of damage caused by earthquakes indicate that large differences in the extent of damage often occur. As observed from some remarkable events, the areas of intense damage can be highly localized, while the amount of damage drastically changes over short distances from the epicentre. These large variations in structural damage can be attributed to different variables, as the upper structure characterization, the local subsoil condition, the nature of the arriving seismic energy, the way the ground shaking is filtered by the structure itself, (Udwadia and Trifunac, 1973). Due to the relatively small number of significant measurements of strong ground shaking caused by close-in earthquakes, little is known about factors that influences ground motion at a site and its effects on the surrounding structures. Considering the numerous of no systematic data collected during the occurred earthquakes and a relevant uncertainty in the expectation of structural responses at a given side, since 1940s a probabilistic description of the main variables used in earthquake-resistant design has been preferred, (Newmark et al, 1971). In the last decades, seismologists and engineers have looked for the perfect shape of design spectra, analysing recorded signals and elaborating them sometimes with a forced probabilistic interpretation. As visible in many modern codes, a uniform hazard is often considered: the resulting acceleration design spectra derive from the never questioned assumptions of having constant acceleration for short period, constant displacements for long periods and constant velocity in the intermediate period range. If Calvi (2018) claims the need to introduce different logics to make design spectra potentially consistent with the experimental evidence, spectral value from recent earthquakes point out the need introduce a more effective design strategy.

## 2 BIRTH AND SPREADING OF RESPONSE SPECTRA IN EARTHQUAKE ENGINEERING

The ground motions recorded at El Centro on 18 May 1940, and mainly the North-South component , have been the main reference until the eighties. Its maximum recorded peak ground acceleration of 0.35g (Figure 1), corresponding to a maximum spectral acceleration of 0.90g at 0.50 s and a maximum spectral displacement of 27.25 cm at 2.80 s, (Figure 2), have influenced the definition of seismic design actions in all building codes, until today.

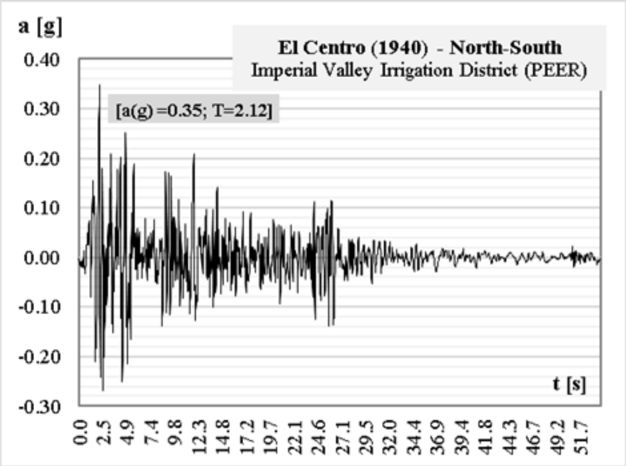

Figure 1. El Centro Earthquake(1940) Accelerogram for North-South Component

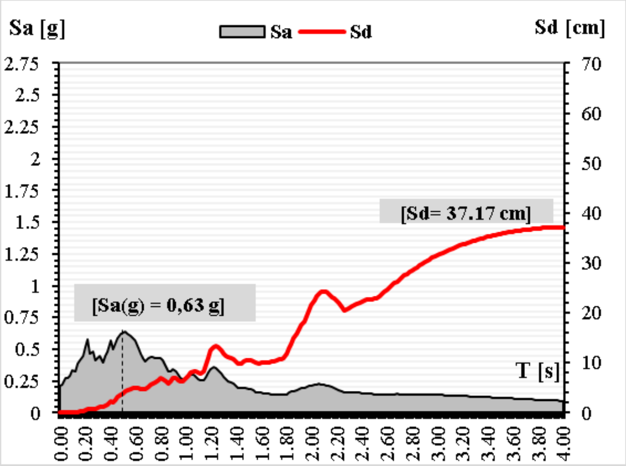

Figure 2. El Centro Earthquake. Design spectra in term of acceleration and displacement.

### 2.1 *Probabilistic method in earthquake-resistant design*

Instead of reflecting the results of few records, building codes opt for design spectra that represent a uniform hazard: they predict spectral acceleration whose probability of exceedance at different periods is function of source and of propagation parameters. This method, often mechanically practiced, goes beyond the complex of variables that govern effectively the estimation of strong-motion characteristics for seismic risk assessment and earthquake-resistant design. However this approach derived from experimental results and accurate analytical formulation of data from real earthquakes.

The concept of elastic response spectrum, that synthetizes the peak response of all possible single-degree of freedom system to a particular component of ground motion, is deep-rooted into earthquake engineering, (Chopra, 2007) (Chopra, 2012). This method results from the earliest experimentations in 1926 by Suyehiro, first Director of the Earthquake Research Institute at Imperial Tokyo, concerning his so-called “seismic vibration analyzer”: this pioneering system was made of 13 compound pendulum elements having different natural vibration periods. When earthquake occurred, the motion of each pendulums was traced on a rotating drum, reproducing its deformation response: the corresponding peak value gave a point on the displacement response spectrum( Suyehiro, 1926).

This system anticipated the development of response spectrum theory, whose earliest analytical formulation appeared in Biot’s PhD Thesis (Biot, 1932). Biot himself later presented the application of a general method of analysis of earthquake-induced stresses for a simple oscillator, developed at the California Institute of Technology in 1932 (Biot, 1941). This method was based on the possibility of drawing a curve that represented “some kind of harmonic analysis of the earthquake, where the acceleration intensity is plotted as a function of the frequency”, later defined “earthquake spectrum”. With the same intent of computing the response of a simple oscillator to arbitrary ground motion, the contemporary Housner (Housner, 1941) (Housner, 1941)]firstly gave a representation of displacement and acceleration spectra, elaborating the East-West component of the ground motion recorder at Los Angeles subway terminal during the earthquake of 2 October, 1933, Figure 3. Form these first evaluations, he estimated that the maximum possible ground acceleration could be nearly 0.30g.

To be valid, this analytical approach required a great amount of data, not always available at the time. Housner himself recognized that, apart from the available data, many other external factors could influence the way an arbitrary earthquake and the corresponding seismic response can be simulated. They can pass from the mechanisms that produce tectonic motions (as slips along geologic faults) to the earthquake duration, as the total time of ground shaking for the arrival of the seismic wave to the return to the environmental conditions.

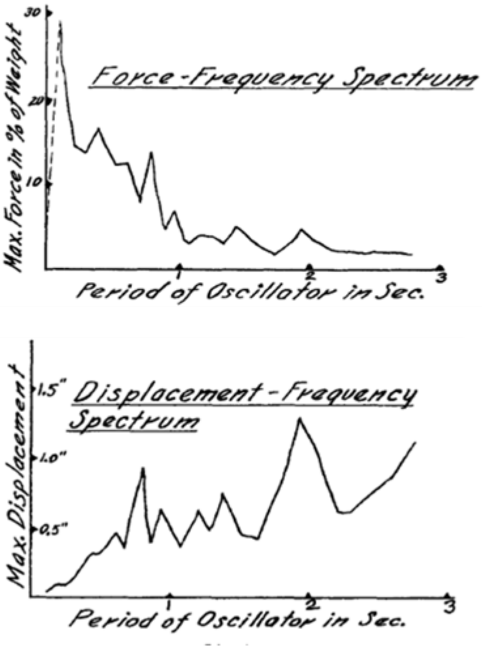

Figure 3. Normalized pseudo-acceleration (a/g) (above) and Deformation response spectrum (upper), for SW component of Los Angeles ground motion (October 2, 1933) © Housner

Assuming that fault slips cause earthquake and adopting certain assumption for rock properties, Housner (Housner,1965)concluded that the maximum possible ground acceleration is 0.50g. with these assumption a maximum value for the ground acceleration cannot be established if it is supposed that earthquake as a consequence of a phase change in rocks. On the contrary, according to Newmark, as function of rock properties, a maximum horizontal ground velocity can be computed in the range 1 m/s – 3 m/s, (Newmark, 1967). Even if the main expectation for designers is to define the intensity or the local destructiveness of the earthquake by a single number, as later argued by Bommer and Pereira (Bommer and Pereira, 2000), itis difficult to characterize the nature of strong motion by using only one parameter . The widely used one in seismic design is the acceleration response spectra, even if structural damage during earthquakes is not controlled exclusively by the transmitted accelerations but it is correlated to the induced displacements. The evaluation of the expected levels of seismic ground motion as the base input to earthquake resistant design cannot prescind from this evaluation.

## 3 POST-KOBE APPROACH TO EARTHQUAKE-RESISTANT BUILDINGS AND THE “NEXT GENERATION” OF SEISMIC ISOLATION

### *3.1 Lesson from noticeable earthquakes of 1980-1990’s*

Strong motions occurred from the end of 1980’s and the mid-90’s firstly revealed to the world the destructive potential of earthquakes, revealing unexpected spectral displacements greater than 60 cm and spectral acceleration higher than 0.65g for T> 2.50 s. In this regard, Mexico City earthquake (1985), Figure 4 and Figure 5, was characterized by Mw 8.1; it counted 3,000 demolished buildings while other 100,000 suffered serious damage; 10,000 people lost their lives, 30,000 were injured and thousands more were left homeless.

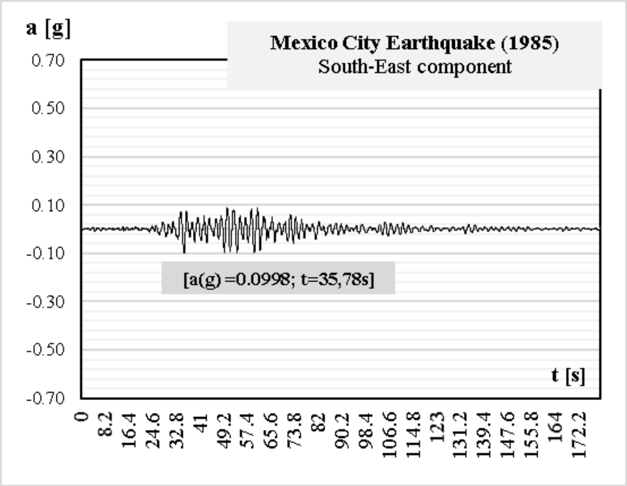

Figure 4. Mexico City Earthquake (1985). Accelerogram for South-East Component

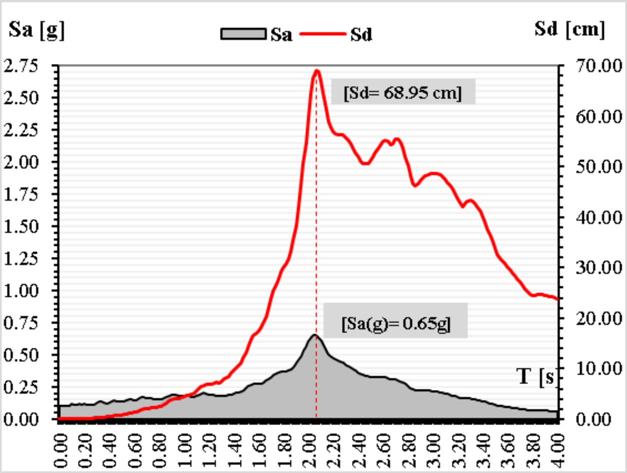

Figure 5. Mexico City Earthquake. Design spectra in term of acceleration and displacement.

On the contrary, a PGA not exceeding 0.10g was recorded by stations at the time, while a maximum spectral displacement of 68.95 cm has been estimated. This underlines the insufficient number of station at time to describe really the destructiveness of this phenomenon.

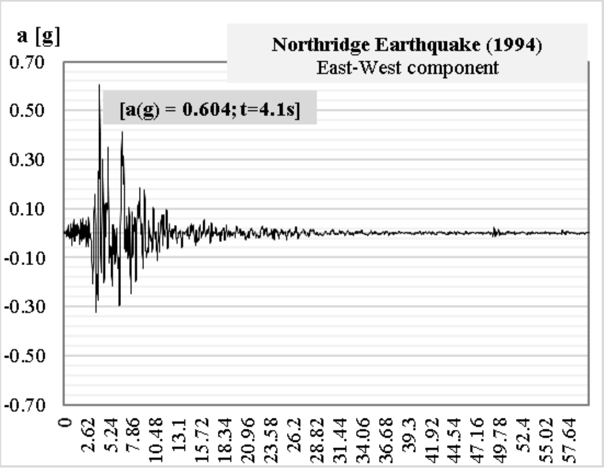

Figure 6. Northridge Earthquake (1994). Accelerogram for East-West Component

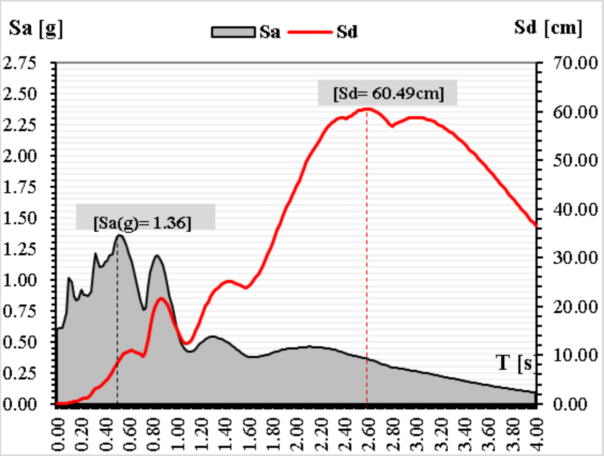

Figure 7. Northridge Earthquake (1994). Design spectra in term of acceleration and displacement.

Northridge earthquake (1994), Figure 6 and Figure 7, with Mw 6.9, was the worst earthquake in the Los Angeles basin since the San Fernando earthquake in 1971, which had a 6.7 magnitude. The number of fatalities was 57; about 9000 people were injured. The fact that the earthquake occurred at 4:30 a.m. minimized the death toll. A total damage for $44 billion was counted (Petak, Elahi, 2001). A maximum PGA of 0.60g was documented at the site, while the elaboration of recorded data gave a maximum spectral acceleration of 1.36g at T=0.52 s and a spectral displacement of 60.49 cm at 2.6 s.

As in the previous case of Mexico City strong motion, the estimated spectral displacement and acceleration are about twice those ones computed for the referring El Centro earthquake.

Kobe earthquake (1995), Figure 8 and Figure 9, that registered 6.9 Mw, left 6,425 dead, injured 25,000, displaced 300,000 people, damaged or destroyed 100,000 buildings and caused at least $132 billion worth of damage.

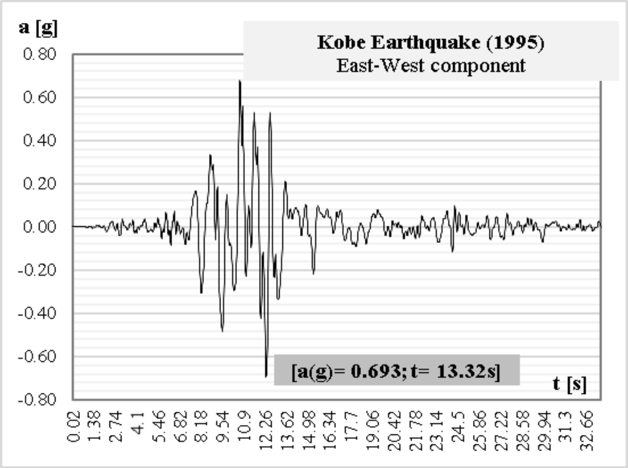

Figure 8. Kobe Earthquake (1995). Accelerogram for N-S Component

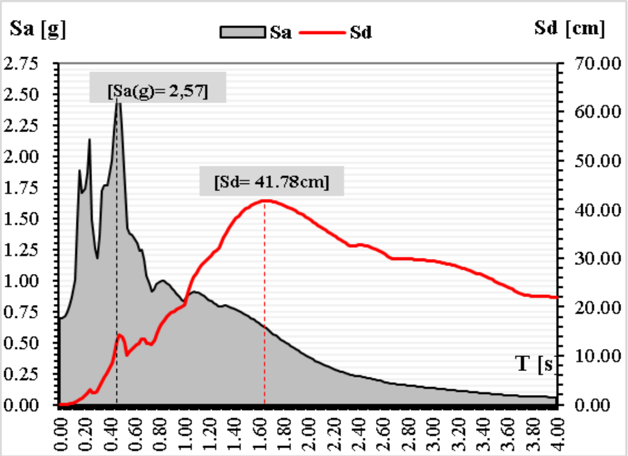

Figure 9. Kobe Earthquake. Design spectra in term of acceleration and displacement

The earthquake involved about 2.5% of Japanese national income, becoming the most expensive natural disasters in history. A maximum PGA of 0.69g was documented at the site, while the elaboration of recorded data has given a maximum spectral acceleration of 2.57g at T=0.17s and a maximum spectral displacement of 41.78 cm at T=1.66 s. Also in this case, the destructiveness of the earthquake pointed out the need to counteract unpredictable high spectral values (acceleration, velocity and displacement).

This justifies the concurrent need to improve of technologies that make building able to counteract ever larger spectral values not foreseen until that time neither in codes nor in scientific community. In this regard, we can notice that since 1990’s the number of isolated buildings has increased rapidly. The positive feedback in Base Isolation System (BIS) during previous destructive events encouraged the spread of this technology at the end of the 20th century. In Japan, the construction of base isolated buildings has increased significantly since the 1995, reaching over 150 annual constructions (Nakashima, 2004). Looking at BIS applications in the U.S.A. it is easy to note that in the decade (1995 – 2004) a significant boost to improve this technology can be seen in retrofits rather than in new building constructions, (De Luca, Mele, 1997). Compared to the earliest applications at the beginning of 1980's (Kelly, 1990), the effort in base isolation design in U.S.A. was justified by the devastating effects seen during Loma Prieta (1989) and Northridge (1994) earthquakes.

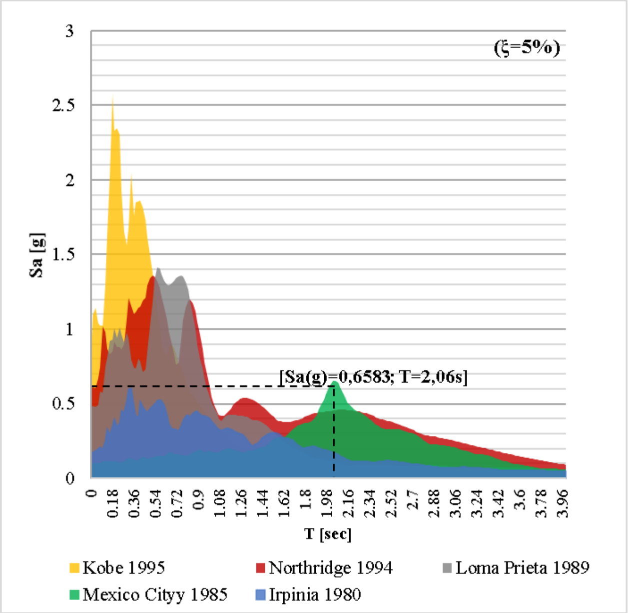

Figure 10. 1980-1990's main EQs. Spectral accelerations

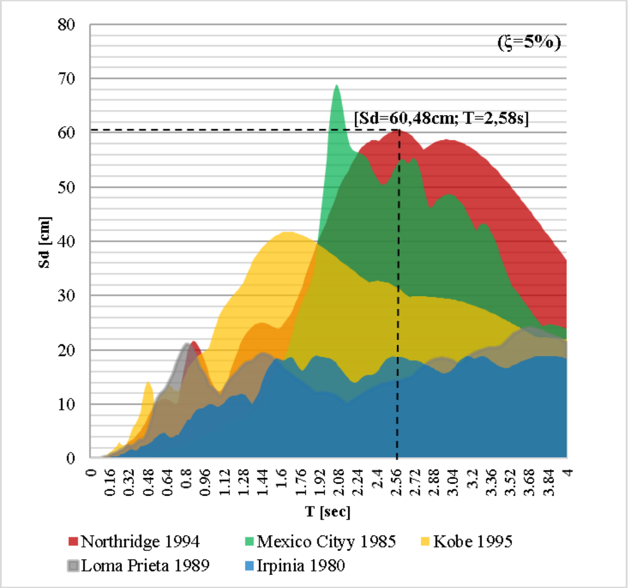

Figure 11. 1980-1990's main EQs. Spectral displacement

A more detailed description of the impact of these destructive phenomena derived from a great accuracy in recording data on site: a 0.658g peak spectral acceleration at T= 2.06 s recorded during Mexico City earthquake, or 60 cm peak spectral displacement recorded during Northridge earthquake, demonstrated to the world unexpected spectral acceleration and displacement values.

To face them, Figure 10 and Figure 11, it was now necessary to improve the design the design of earthquake resistant structures, moving to large design periods and to face very large design displacements, (De Luca, Guidi, 2019).

By taking into account all these factors, it's easy to recognize that building codes need to be reviewed, valuing an appropriate design strategy for earthquake resistant structures.

### *3.2 Attitude of rules in force: the Italian case*

Even though all codes include provisions for dynamic response analysis, the seismic action is generally calculated in accordance to an acceleration design response spectrum, defined for a fixed damping percentage. The design spectrum, defined in accordance to the specific seismicity of analysed region and to the established return period of the considered seismic load, generally consists in of two (eventually three) portions: a uniform acceleration portion for short period, a uniform velocity portion (eventually followed by a constant displacement portion) in the longer-range period. Although contemplating time history analysis method that gives the possibility to value the dynamic response of structures also on the base of real earthquake records appropriately scaled, in order to define design spectra, current building codes still refer to the original a probabilistic approach, despite of the destructive impact of recent phenomena. This idiosyncrasy is clearly visible comparing the results from the elaboration of recorded data from well-known earthquakes occurred in the past three decades and the elastic acceleration and displacement spectra defined in accordance to Italian design code (NTC 2018). These last ones have been valued for the so-called "SLC", i.e. the "Collapse Limit State", characterized by a return period of 975 years, i.e. the expected earthquake has a probability of occurrence of 5% referred to a period of 50 years: SLC represents the worst scenario that current building code can predict. It is defined considering the specific seismicity of each involved area, in regard to the latest seismic zoning, approved by the Italian Department of Civil Protection - Presidency of the Council of Ministers since 1982. In this regard, it is well known that the OPCM 3274/2003 led to update the current seismic zoning of Italian regions, providing four different zones (having respectively a maximum ag of 0.35g, 0.25g, 0.15g and 0.05g). Successive dispositions have not modified the aforementioned maximum acceleration limits, even if a wider use of seismic instruments from the end of the nineteenth century and monitoring networks in the twentieth century finally have provided input for studies into seismic characterisation in Italy.

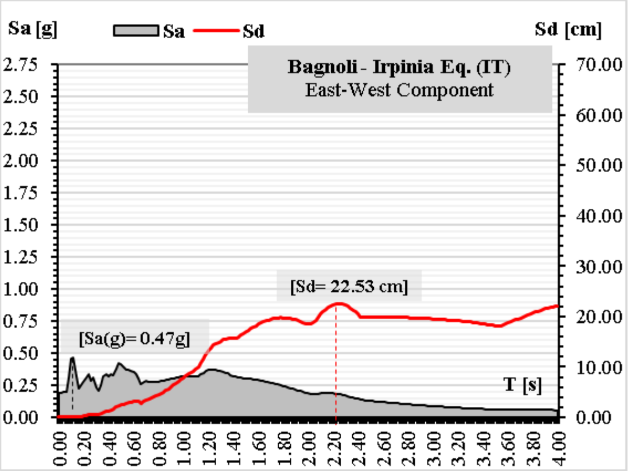

Figure 12. Irpinia Earthquake (IT) – Bagnoli site (1980). Design spectra in term of acceleration and displacement.

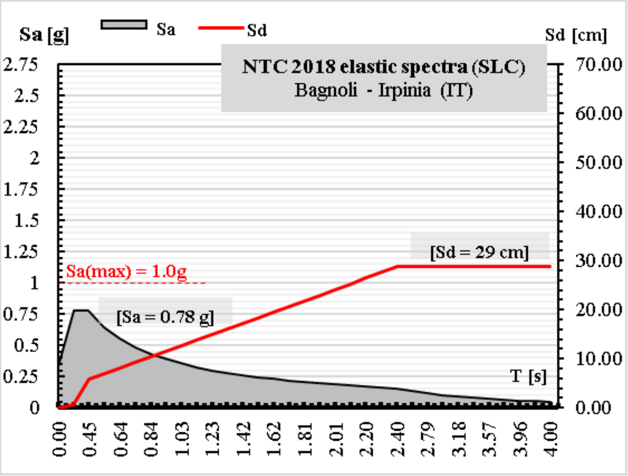

Figure 13. Irpinia Earthquake (IT) – Bagnoli site (1980). Elastic spectra in accordance to NTC 2018.

The existing monitoring network at 1980 in the South Italy was not sufficient to correctly describe the destructiveness of Irpinia Earthquake, with Mw 6.9, Figure 12: the recorded PGA at site (Bagnoli) was 0.19g, while the devastating earthquake left at least 2,483 people dead, 7,700 injured, and 250,000 homeless. The lack of information led to underestimate the severity of the occurred ground motion, in terms of spectral displacement and acceleration, also in comparison to the expected values defined in accordance to NTC2018, Figure 13.

Studies concerning seismic hazard in Italy was later improved, above all since the beginning of 21th century: Puglia and Molise earthquakes in 2002 led to the enactment of the aforementioned OPCM 3274/2003, according to which seismic hazard involves each area of Italian peninsula. Five year later, L'Aquila earthquake (2006) showed a PGA of 0.65g, about twice the upper limit of the original seismic zoning.

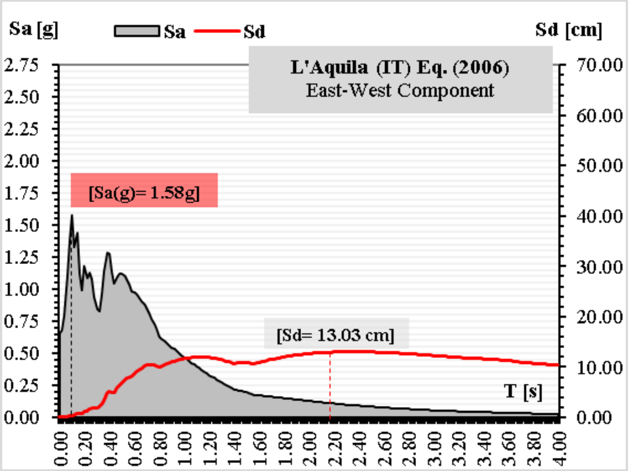

Figure 14. L'Aquila (IT) Earthquake (2006). Design spectra in term of acceleration and displacement.

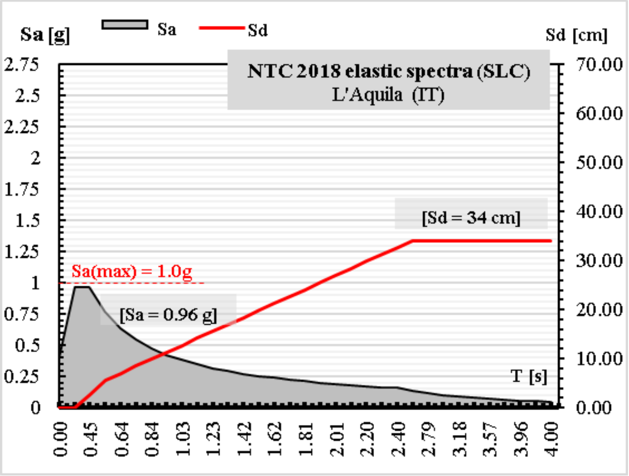

Figure 15. L'Aquila (IT) Earthquake (2006). Elastic spectra in accordance to NTC 2018.

Having a Mw of 6.3, this strong motion left 308 dead, more than 1,500 injured and about 65,000 homeless, becoming the deadliest earthquake to hit Italy since the aforementioned 1980 Irpinia earthquake. The elaboration of recorded data, Figure 14, has given a maximum spectral acceleration of 1.58g at T=0.10s against 0.96g obtained from the elastic acceleration spectrum defined in accordance to the current Italian building code, Figure 15.

The same incompatibility between the expected spectral values and the effective ones is clearly visible in the case of the recent Amatrice Earthquake (2016), occurred in the central Italy, with epicentre close to Accumuli, in an area near the borders of the Umbria, Lazio, Abruzzo and

Marche regions. This earthquake, measuring Mw 6.2, caused about 299 deaths, 388 injured, leaving more than 4,500 people homeless. A maximum PGA of 0.86g has been recorded in the city of Amatrice alone.

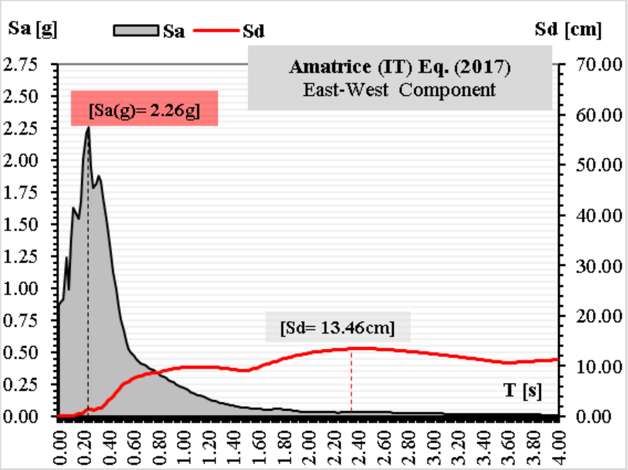

Figure 16. Amatrice (IT) Earthquake (2016). Design spectra in term of acceleration and displacement.

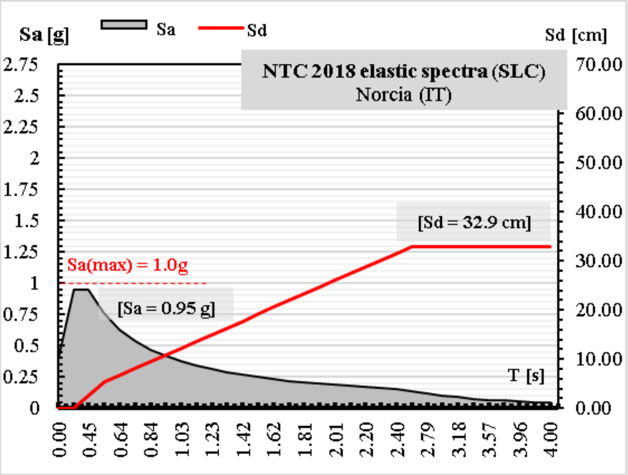

Figure 17. Amatrice (IT) Earthquake (2016). Elastic spectra in accordance to NTC 2018.

The earthquake caused the total destruction of the city itself. Elaborations of data recorded at site return a value of maximum spectral acceleration of 2.26g, Figure 16, at 0.24s, more than four time the maximum acceleration given by the elastic spectrum, defined in accordance to NTC2018, Figure 17.

Also Norcia was involved by the same strong motion (2016), recording a PGA of 0.79g. Elaborations of data recorded on site, Figure 18, return a maximum spectral acceleration of 4.22g at 0.14s against 0.95g obtained from the elastic acceleration spectrum defined in accordance to the current Italian building code, Figure 19.

Previous analysis remark the need to update the current building code in such a way the effective severity of expected ground motions could be contemplated by the elastic spectra. This approach has been confirmed on worldwide scale, by damaging earthquake recently.

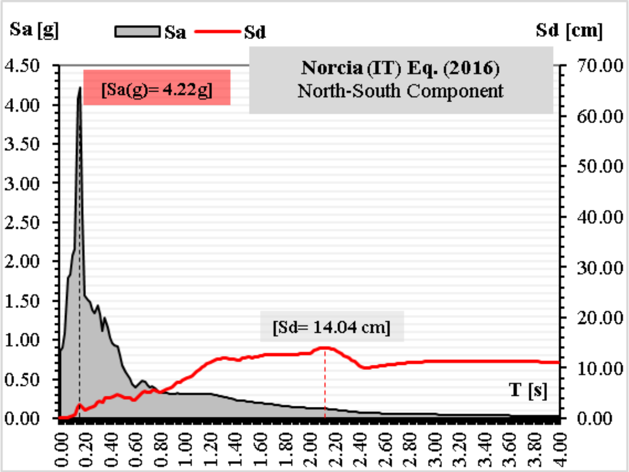

Figure 18. Norcia (IT) Earthquake (2016). Design spectra in term of acceleration and displacement.

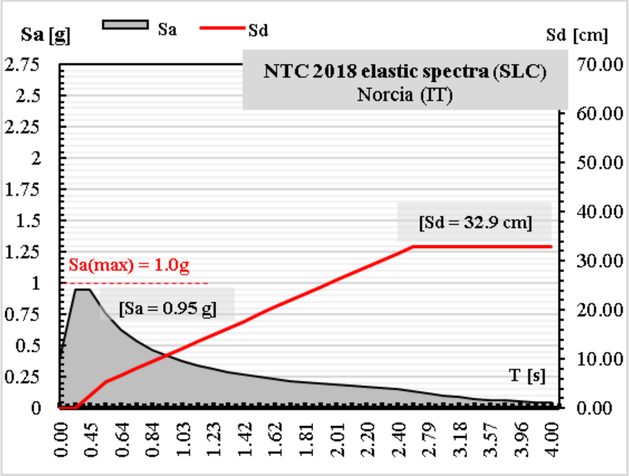

Figure 19. Norcia (IT) Earthquake (2016). Elastic spectra in accordance to NTC 2018.

### *3.3 Lesson from worldwide recent earthquakes and the pioneering approach by Miyazaky*

At the beginning of XXI century, destructive phenomena revealed to the scientific community the need to safeguard structures from unprecedented strong motions, recording unexpected spectral values (in terms of acceleration, velocity and displacement). The common idea of safeguard structure from earthquake by “shifting” the structure itself form the acceleration plateau range loses its validity at the time that the spectral displacement could exceed 90 cm for T>2.50 s.

In terms of design strategy to counteract recent damaging strong motions, a truing point has been marked by Miyazaki (Miyazaki, 2008). After having analysed 26 recent strong earthquakes, he firstly has underlined the need to go beyond the minimum legal regulations that concern the design of earthquake-resistant structures. The purpose of seismic design is to ensure safety against earthquake, as unpredictable natural phenomena, whose induced motion could actually exceed spectral displacements contemplated by codes. Miyazaki's studies start from the comparison of data recorded during 22 strong ground motions, occurred in the past 30 years, in the U.S.A., Taiwan and Japan, and data of the 4 simulated long-period motions, theoretically derived (AIJ, 2007). Among the recorded motions, it is mentioned the Taiwan Chi Chi earthquake (1999) with an unexpected peak ground displacement (PGD) of 289 cm.

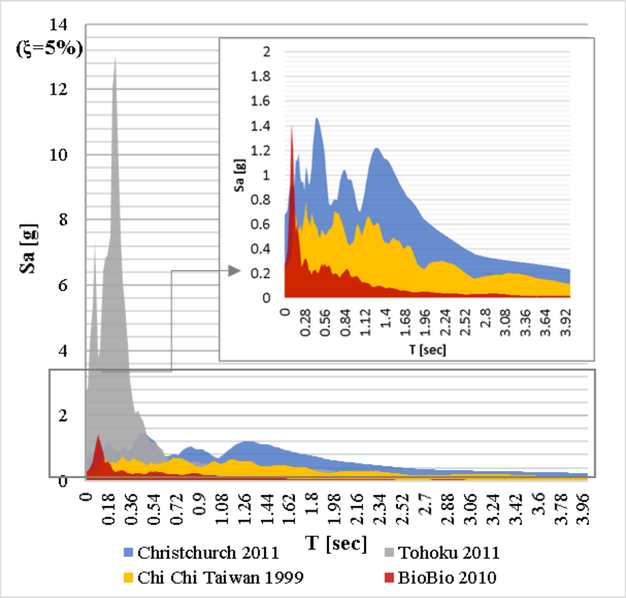

Figure 20. 2000 -2010 main EQs: spectral accelerations

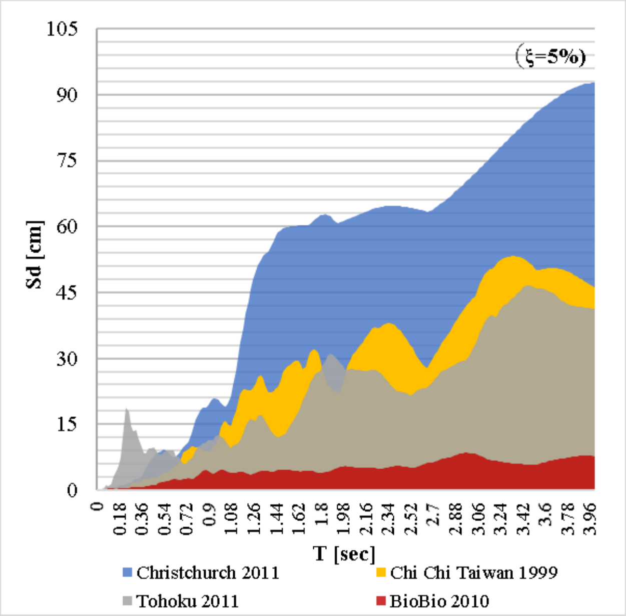

Figure 21. 2000 -2010 main EQs: spectral displacements

To counteract these unprecedented spectral values of displacement, velocity and acceleration Miyazaki suggests that the optimum design condition might be obtained for a base isolation system that guarantees a vibration period Tiso greater than 10 s, having a damping factor from 80% to 100%. Considering that in the longer period range the design displacement grows while the input energy decreases significantly, assuming T greater than 10 s would provide the maximum advantages for this ideal isolation system, especially to respond to high spectral value of acceleration, velocity and displacement. Later on, more destructive earthquakes have occurred such as Tohoku (2011) or Christchurch (2011, δmax> 90 cm) earthquakes (Carr, 2011), (Wotherspoon et al., 2011), (Kam and Pampanin, 2011), (Uma et al., 2013). This results in the need for more effective design strategy, considering these unprecedented values of spectral acceleration, up to 12g, or of spectral displacements, up to 1 m ), Figure 20 and Figure 21 (De Luca, Guidi, 2019).

Table 1. Deadliest and most destructive earthquakes in the last decades

| year | Earthquake | Mw | deaths |
|---|---|---|---|
| 2010 | Haiti | 7 | 222570 |
| 2008 | Eastern Sichuan, China | 7.9 | 87587 |
| 2005 | Pakistan | 7.6 | 86000 |
| 2004 | Sumatra, Indonesia | 9.1 | 227898 |
| 1990 | Western Iran | 7.4 | 50000 |
| 1976 | Tangshan, China | 7.5 | 255000 |
| 1970 | Chimbote, Perù | 7.9 | 70000 |
| 1948 | Ashgabat, Turkmenistan | 7.3 | 110000 |
| 1923 | Kanto, Japan | 7.9 | 142800 |
| 1920 | Haiyuan, Ningxia , China | 7.8 | 200000 |
| 1908 | Messina, IT | 7.2 | 72000 |
| 1755 | Lisbon, Portugal | 8.7 | 70000 |
| 1693 | Sicily, Italy | 7.5 | 77000 |
| 1556 | Shensi, China, | 8 | 830000 |

However, looking at the worldwide distribution of earthquakes with magnitude greater than 8, occurred in the last decades, Figure 22 and Table 1, it is easy to note that they correspond enough to the largest strong motions by life losses , Figure 23, even if recorded data o site sometimes revealed a less catastrophic scenario than it has been effectively. This is attributable to the shortage of signals that can be recorded actually, underling the need to intensify the seismic network, above all in earthquake-prone countries.

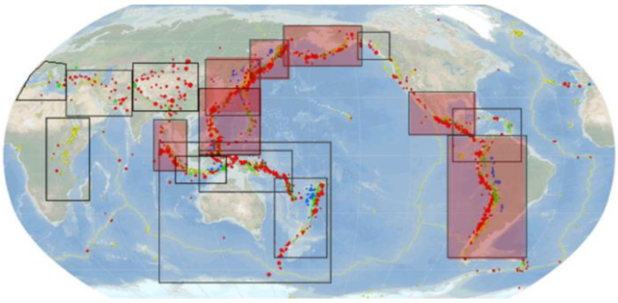

Figure 22. Zones affected by EQs with Mw>8

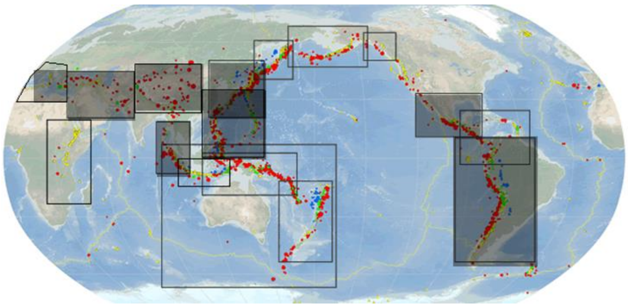

Figure 23. Zones affected by the deadliest EQs

## 4 CONCLUSIVE REMARKS

Comparing the elaborations of data from recent earthquakes with the expected spectral values defined in accordance to the probabilistic approach proposed by current building codes worldwide, a certain idiosyncrasy can be read. This means that future earthquakes cannot only be described only in terms of probability because of the greater uncertainty about structural response at a given site. Current building codes require to be updated, to take into account the destructiveness of earthquake effectively occurred. In particular, the acceleration could not be the only parameter assumed in defining a correct design strategy for seismic resistant structures: recent recorded data remark the severity of displacements, able to exceed 200 cm.

However, these humongous values cannot be effectively counteracted: it would be impossible to design a structure able to counteract a seismic force at least 10-time greater its own weight or to accommodate displacements greater than devices dimensions: therefore, a better quality in construction and a higher accuracy in details are required to contribute to structural safety.

## REFERENCES

Architectural Institute of Japan, 2007. *Structural Response and Performance for Long Period Seismic Ground Motio*n. Chapter II and Section III-6.

Biot M.A., 1932. *Transient Oscillations in elastic system.* PhD Thesis, Civil Engineer Department, California Institute of Technology, Pasadena, CA.

Biot M.A., 1941. *A Mechanical analyzer for the prediction of earthquake stresses*. Bulletin of Seismological Society of America, 1941; 31:151-171.

Bommer J.J., Martìnez-Pereira A., 2000. *Strong-Motion Parameters: Definition, Usefulness and Predictability.* Proceedings the 12th World Conference on Earthquake Engineering, Auckland, New Zealand.

Calvi G.M., 2018. Revisiting design earthquake spectra. Earthquake Engineering and Structural Dynamics. 2018; 1-17. Wiley Online Library. DOI: 10.1002/eqe.3101.

Carr A.J., 2011. I*nelastic Response Spectra for the Christchusrch Earthquake Records.* Report to the Canterbury Earthquakes Royal Commission.

Chopra A.K., 2007. *Elastic Response Spectrum: A Historical Note. Earthquake Engineering and Structural Dynamics*; 36:3-12. Wiley Online Library. DOI: 10.1002/eqe.609

Chopra A.K., 2012. *Dynamics of Structures. Theory and Applications to Earthquake Engineering*. 4th Edition. Prentice Hall, Pearson.

De Luca A., Mele E., 1997. *Base Isolation and Energy Dissipation General Report*. Proceedings of the Second International Conference STESSA '97, Behaviour of Steel Structures in Seismic Areas, Kyoto, Japan, pp. 683 – 699.

De Luca A., Guidi L.G., 2019. *State of art in the worldwide evolution of base isolation design.* Soil Dynamics and Earthquake Engineering. 125 (2019) 105722

Housner, G.W., 1941. *An Investigation of the effects of Earthquakes on Building*s. PhD Thesis, Civil Engineer Department, California Institute of Technology, Pasadena, CA.

Housner, G.W., 1941. *Calculating the Response of an Oscillator to Arbitrary Ground Motion.* Bulletin of Seismological Society of America, 1941; 31:143-149.

Housner, G.W., 1965. *Intensity of ground shaking near the causative fault.* Proceedings 3WCEE, 1, 81-94.

Kam W.Y, Pampanin S., 2011. *The seismic performance of RC buildings in the 22 February 2011 Christchurch earthquake.* Structural Concrete 12. No.4, pp. 223 – 233.

Kelly J.M, 1990. *Base isolation: Linear Theory and Design*. Earthquake Spectra, 1990; Vol.6, No.2, pp. 223–244.

Miyazaki M., 2008. *The Next generation of seismic isolation. Going beyond seismic design dominated by earthquakes.* Journal of Disaster Research. Vol.3 No.6, pp. 479-502.

Nakashima M., Pan P., Zamfirescu D., Weitzmann R., 2004. *Post-Kobe Approach for Design and Construction of Base-Isolated Buildings*. Journal of Japan Association for Earthquake Engineering, Vol.4, No.3 (Special Issue).

Newmark N.M, 1965. *Problems in Wave Propagation in Soil and Rock.* Symposium Wave Propagation and Dynamic Properties of Earth materials. University of New Mexico, Alburquerque, 7-26,

Newmark N.M.,Rosenblueth E.,1971. *Fundamentals of earthquake engineering*. Prentice-Hall, Englewood Cliffs, N.J.

Petak W., Elahi S., 2000. *The Northridge Earthquake, USA and its Economic and Social Impacts*. Euro Conference on Global Change and C atastrophe Risk Management Earthquake Risks in Europe, IIASA, Laxenburg Austria.

Stover C.W., Coffman J.L.,1993. *Seismicity of United States, 1568-1989*, U.S. Geological Survey Professional Paper 1527, UNITED States Government Pronting Office.

*Suyehiro* K., 1973. *A Seismic Vibration Analyzer and the Records obtained therewith*. Bulletin of Earthquake Research Institute – University of Tokyo 1926; 1:59-64.

Udwadia F.E., Trifunac M.D., 1973. *Comparison of earthquake and microtremor ground motions in El Centro, California*. Bulletin of Seismological Society of America. Vol 63, No. 4, pp. 1227-1257.

Uma S.R., Dhakal R.P., Nayerloo M., 2013. Vulnerability Assessment of Christchurch Buildings in Canterbury earthquakes. GNS Science Report 2013/20.

Wotherspoon L., Bradshaw A., Green R.A., Wood C., Palermo A., and Cubrinovski, M, 2011. *Performance of Bridges during the 2010 Darfield and 2011 Christchurch Earthquake*, Seismological Research Letters, N.82, pp.950-964.