A NOTE ON SIGNIFICANT STRONG-MOTION DURATION DEFINITIONS

Abhishek Banerjee
Formerly Graduate Student
Dept. of Civil Engineering, Indian Institute of Technology, Kanpur 208016, India

Vinay K. Gupta
Professor, Dept. of Civil Engineering, Indian Institute of Technology, Kanpur 208016, India

Abstract

This study looks at a comparison of the 'significant duration' definitions of strong-motion duration of earthquake ground motions. This group of duration definitions is based on normalized energy arrival during the earthquake ground motion, and therefore those definitions are particularly relevant to the studies related to inelastic structural response. The definitions considered here are those by Trifunac and Brady, McCann and Shah, and Banerjee and co-workers. A detailed comparison in case of 6 recorded accelerograms shows that the overall performance of the definition by Banerjee and co-workers is better than that of the definitions by Trifunac and Brady and McCann and Shah.

INTRODUCTION

Strong-motion duration (SMD) of a ground motion refers to the duration during which the ground shaking is most severe and contributes most to the total response of a structural system. It is considered to be a useful ground motion parameter for studies related to structural damage and for parametric studies on strength reduction factors (see, for example, Teran-Gilmore and Jirsa (2004) and Chakraborti and Gupta (2005)). SMD has no unique definition and different researchers have proposed different definitions for applications in different situations. Bommer and Martínez-Pereira (1999) classified these definitions into three generic categories, viz. 'bracketed duration', 'uniform duration' and 'significant duration'. The significant duration definitions consider that portion of the ground motion record which accounts for a particular fraction of the total energy arrival. Therefore, the use of significant duration may be more relevant when it is crucial for the strong-motion segment to correspond to almost the same peak structural response as the original motion. A significant duration definition is also based on the characteristics of the entire motion and defines a continuous time window for the strong-motion phase of the motion (Bommer and Martínez -Pereira (1999)).

Among various 'significant duration' definitions proposed so far, those by Trifunac and Brady (1975) and McCann and Shah (1979) are relatively more popular. The definition of Trifunac and Brady (1975) allocates a fixed fraction (90%) of the total energy arrival to the strong-motion segment and assumes the strong-motion segment to begin after a fixed fraction (5%) of the total energy has arrived. Due to this in-built inflexibility, this definition may result in some part of the strong motion to be missed out at the beginning or at the end of the records with unusually short build-up or decay segments respectively. On the other hand, for those motions where the strong-motion segment is very small, this definition would overestimate SMD. The definition of McCann and Shah (1979) is based on the power input of the ground motion, and may give unreasonably long strong-motion segments if there are small impulses in the portions of weak motion in the beginning or at the end of the record. A new 'significant duration' definition of SMD has been proposed recently by Banerjee et al. (2006) to generalize the definition of Trifunac and Brady (1975) by providing flexibility to the instant at which the strong-motion segment starts and to the amount of energy that should be included in this segment relative to the entire motion.

This study presents a comparison of the relative performances of the SMD definitions by Trifunac and Brady (1975), McCann and Shah (1979), and Banerjee et al. (2006) through six example cases of recorded accelerograms.

SIGNIFICANT DURATIONS: DEFINITIONS

A significant duration is defined as (Bommer and Martínez-Pereira (1999))

$$T_s = T_2 - T_1 \tag{1}$$

where T_1 and T_2 are respectively the initial and final time-points of the strong-motion segment, as measured from the beginning of the ground motion. T_1 and T_2 correspond to certain fractions of the total energy arrival, say E_1 and E_2, respectively, in the ground motion where E_i is given by

$$E_i = \frac{\int_0^{T_i} x^2(t)dt}{\int_0^{T_t} x^2(t)dt} \tag{2}$$

with T_t representing the total length of the ground motion record, x(t). Fig. 1 illustrates such a computation of T_s.

The well-known and most widely-used definition of Trifunac and Brady (1975) considers the strong ground motion taking place in between the threshold energy arrival limits of 5% and 95% (i.e., $E_1 = 0.05$ and $E_2 = 0.95$, giving $\Delta E = E_2 - E_1 = 0.9$), and is thus based on the fixed values of ΔE and E_1. On the other hand, the definition by McCann and Shah (1979) is based on the rate of the energy arrival during the strong-motion segment. This depends on a time-varying function that is defined at an instant as the root-mean-square (RMS) value of the motion from the start to that particular instant. T_2 in this definition refers to the last zero crossing of the derivative of the RMS value while T_1 refers to the last zero crossing for the record reversed in time.

The recently proposed definition by Banerjee et al. (2006) modifies the definition of Trifunac and Brady (1975) by making E_1 and ΔE dependent on the characteristics of the given motion such that the rate of energy arrival over the strong-motion segment is accounted for. Here, we first identify the strong-motion segment of minimum length for a given fraction ΔE of energy arrival by an appropriate choice of T_1 and then compute its length, T_s, for different values of ΔE. This step ensures the maximum rate of energy arrival during the strong-motion phase, and therefore, the value of T_s for $\Delta E = 0.9$ is equal to or smaller than the SMD estimate of Trifunac and Brady (1975). In the next step, we choose a suitable value of ΔE such that it is associated with the maximum local increase in T_s with ΔE. For this, we identify the point of maximum slope change on the (monotonically increasing) T_s/T_t versus ΔE curve by maximizing the ratio of 'average secant' slopes to the immediate right and left. An 'average secant' slope is arbitrarily defined as the mean of secant slopes with respect to 10 points (spaced at ΔE interval of 0.001) in succession to the right/left of the ΔE under consideration. In other words, it is sought to determine ΔE_{SMD} where

$$\Delta E_{SMD} = \max_i \left(\frac{\sum_{j=1}^{10} \tan \phi_{i+j}}{\sum_{k=1}^{10} \tan \phi_{i-k}} \right) \tag{3}$$

Here θ_{i+j} and θ_{i-k} respectively represent the secant slopes of the *j*th point, P_{i+j}, on the right and the kth point, P_{i-k}, on the left of the point P_i (see Fig. 2 for an illustration).

SIGNIFICANT DURATIONS: RELATIVE PERFORMANCES

To evaluate relative performances of the three signficant duration definitions: Trifunac-Brady, McCann-Shah and the one recently proposed (by Banerjee and coworkers), six recorded accelerograms described in Table 1 are considered. The evaluation is based on the visual comparison of the strong-motion segments as identified by the three definitions. Besides the length of the segment, this comparison also looks at the features admitted or missed by a definition vis-a-vis the other definitions. Further, the impact of curtailing the original record to its strong-motion segment on the non-linear response is also examined. In the event of strong-motion segment being properly identified, the curtailment would not lead to significant errors. Therefore, as an additional performance evaluator, non-linear pseudo spectral acceleration (PSA) spectra for the curtailed records (as per the three definitions) are compared with the PSA spectrum obtained for the original record in each case (PSA here refers to the spectral displacement times the initial oscillator frequency squared). For this purpose, (non-degrading) elasto-plastic oscillators having yield strengths as one-fourth of those required for the elastic response, with F-damping (which signifies no effect of non-linear behaviour on damping), and having a constant damping ratio of 5% are considered.

Fig. 3 shows the results for the 1951 Imperial Valley motion (Record No. 1) where the build-up segment of the accelerogram is missing and the decay segment is rather long without necessarily carrying significant energy. Due to this, the strong-motion segment as per the Trifunac-Brady definition, starting at 0.36 sec, misses the two large initial impulses, and ends up including a significant part of the decay segment. Though the Trifunac-Brady definition leads to the longest strong-motion segment, this does not truly represent the original accelerogram as shown by the large errors in the non-linear PSA spectrum for this segment. The McCann-Shah definition correctly identifies the beginning of the strong-motion segment but it also includes a part of the decay segment, and thus, predicts a longer strong-motion segment. The recently proposed definition misses the impulse between 16-17 sec, but is still able to identify a reasonable strong-motion segment.

Similar is the case with the 1957 Southern California motion (Record No. 2) as shown in Fig. 4, but here the McCann-Shah definition correctly identifies the strong-motion segment. In this case, the single impulse at 0.1 sec into the motion constitutes about 45% of the total energy input and thus leads to a poor fit of the PSA spectrum for Trifunac-Brady segment with the PSA spectrum for the original record.

The 1954 Lower California motion (Record No. 3) shown in Fig. 5 has a build-up segment in the first 12 sec, while the strong-motion segment gradually decays after another 10 sec. In the absence of a clear end point for the strong-motion segment, the Trifunac-Brady definition identifies the shortest and most reasonable strong-motion segment. The recently proposed definition does not perform so well due to the inclusion of a longer decay segment, and identifies a 60.12 sec long strong-motion segment as compared to the 48.68 sec long segment by the Trifunac-Brady definition. The McCann-Shah definition identifies 71.98 sec long segment in a 77.74 sec long record and thus gives an unreasonably long segment. This happens due to small but locally significant peaks at 1.60 sec from the beginning and 3.58 sec before the end of the record. The McCann-Shah definition incorrectly identifies those as the start and end points respectively. This problem is also observed in the case of Record No. 5.

Fig. 6 presents the case of 1962 Northern California motion (Record No. 4) with a short build-up segment, and the strong-motion segment starting with two large impulses. Here, the Trifunac-Brady definition misses the impulses due to its inflexibility with the energy allocation for the the build-up segment. On the other hand, the recently proposed and McCann-Shah definitions incorrectly and entirely include this segment. However, whereas the McCann-Shah definition works well in locating the end-point of the strong-motion segment, the Trifunac-Brady definition considers a portion of the decay segment as well. The recently proposed definition includes even a longer portion of the decay segment thus resulting in a longer duration than the other two definitions.

The 1968 Borrego Mountain motion (Record No. 5) is characterized by the absence of a decay segment as shown in Fig. 7. Though the rate of energy arrival decreases after about 50 sec, it is still significant enough for the remaining part of the motion to be included in the strong-motion segment. As a result, the Trifunac-Brady definition leads to a somewhat premature termination of the strong-motion segment and thus to the smallest value of SMD. The McCann-Shah definition in this case includes a large part of the 19 sec long build-up segment and thus leads to the largest duration estimate. The recently proposed definition on the other hand includes only a small part of the build-up segment and thus identifies the most reasonable strong-motion segment.

Finally, the case of 1980 Livermore Earthquake motion (Record No. 6) shown in Fig. 8 is considered. This motion is characterized by three distinct bursts of energy: first occuring in the beginning of the motion, second around 5 sec, and the third one around 58 sec. The second burst of energy is the longest one lasting for about 11 sec, while the other bursts do not last for more than 2 sec each. The Trifunac-Brady definition fails to include the shorter bursts of energy, and thus leads to smaller estimate of SMD. The other two definitions are able to include all three bursts of energy and to identify approximately the same strong-motion segment. A comparison of the PSA spectra in this case shows that ignoring the shorter bursts of energy may lead to small errors in the oscillator response, particularly for $T < 0.4$ sec.

It follows from the above discussion that both Trifunac-Brady and McCann-Shah definitions may fail considerably in some situations. Whereas the Trifunac-Brady definition fails at times to respond to the situations of abnormally long or short buildup and decay segments due to its inflexible energy allocations to various segments, the McCann-Shah definition predicts too high SMD values in some cases. In the latter case sufficient room is usually left for further curtailment. The definition proposed by Banerjee et al. (2006) on the other hand identifies those strong-motion segments which truly represent the original motions without being 'too long'. In some cases, there may be a scope for further curtailment, but only rarely the segments identified by this definition include significantly long build-up or decay segments of the record.

CONCLUSIONS

A new 'significant duration' definition of the strong-motion duration has been evaluated vis-a-vis two existing definitions. Through a few example cases, it has been observed that the definition proposed by Banerjee et al. (2006) offers a significant improvement over the duration defined by Trifunac and Brady (1975), and a moderate improvement over the definition by McCann and Shah (1979) in most situations. This may overpredict the duration in a few situations but only marginally. The new definition is specifically useful for those applications in which the strong-motion segment is deemed to replace the parent motion.

REFERENCES

Banerjee, A., Karmakar, D. and Gupta, V.K. (2006). A new definition of significant strong motion duration, Earthq. Eng. Struct. Dyn. (submitted).

Bommer, J.J. and Martínez -Pereira, A. (1999). The effective duration of earthquake strong motion, J. Earthq. Eng., 3(2), 127-172.

Chakraborti, A. and Gupta, V.K. (2005). Scaling of strength reduction factors for degrading elasto-plastic oscillators, Earthq. Eng. Struct. Dyn., 34, 189-206.

McCann, M.W. and Shah, H.C. (1979). Determining strong motion duration of earthquakes, Bull. Seism. Soc. Amer., 69(4), 1253-1265.

Teran-Gilmore, A. and Jirsa, J.O. (2004). The concept of cumulative ductility spectra and its use within performance-based seismic design, ISET J. Earthq. Tech., 41(1), 183-200.

Trifunac, M.D. and Brady, A.G. (1975). A study on the duration of strong earthquake ground motion, Bull. Seism. Soc. Amer., 65(3), 581-626.

Table 1 – Particulars of Earthquake Records Used

Record No.	Earthquake	Site	Component
1	Imperial Valley, 1951	Imperial Valley Irrigation District, El Centro	North
2	Southern California, 1957	Navy Research and Evaluation Lab, San Diego	West
3	Lower California, 1954	Imperial Valley Irrigation District, El Centro	North
4	Northern California, 1962	Federal Building, Eureka	S11E
5	Borrego Mountain, 1968	Engineering Building, Santa Ana	S04E
6	Livermore, 1980	Fidelity Savings, Walnut Creek	East

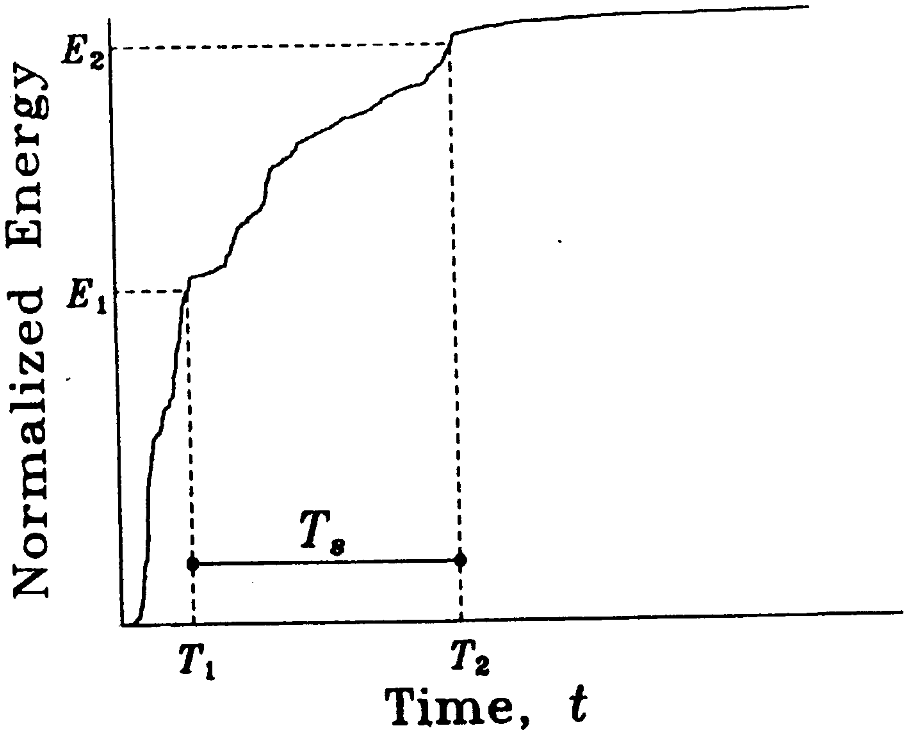


Figure 1 -Schematic Variation of Normalized Energy with Time.

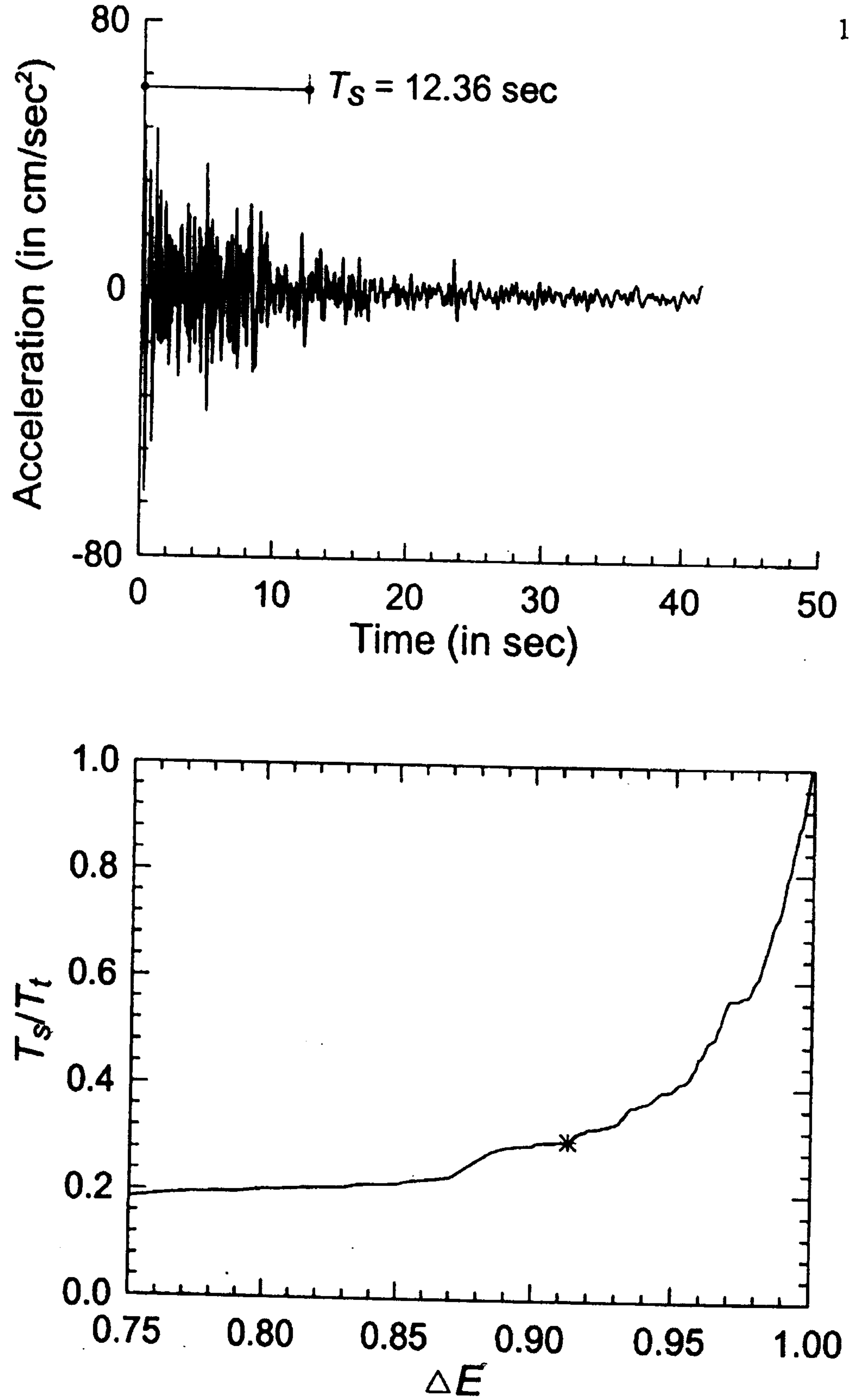


Figure 2 -Illustration of the Method to Calculate Average Secant Slope at the Point Pi.

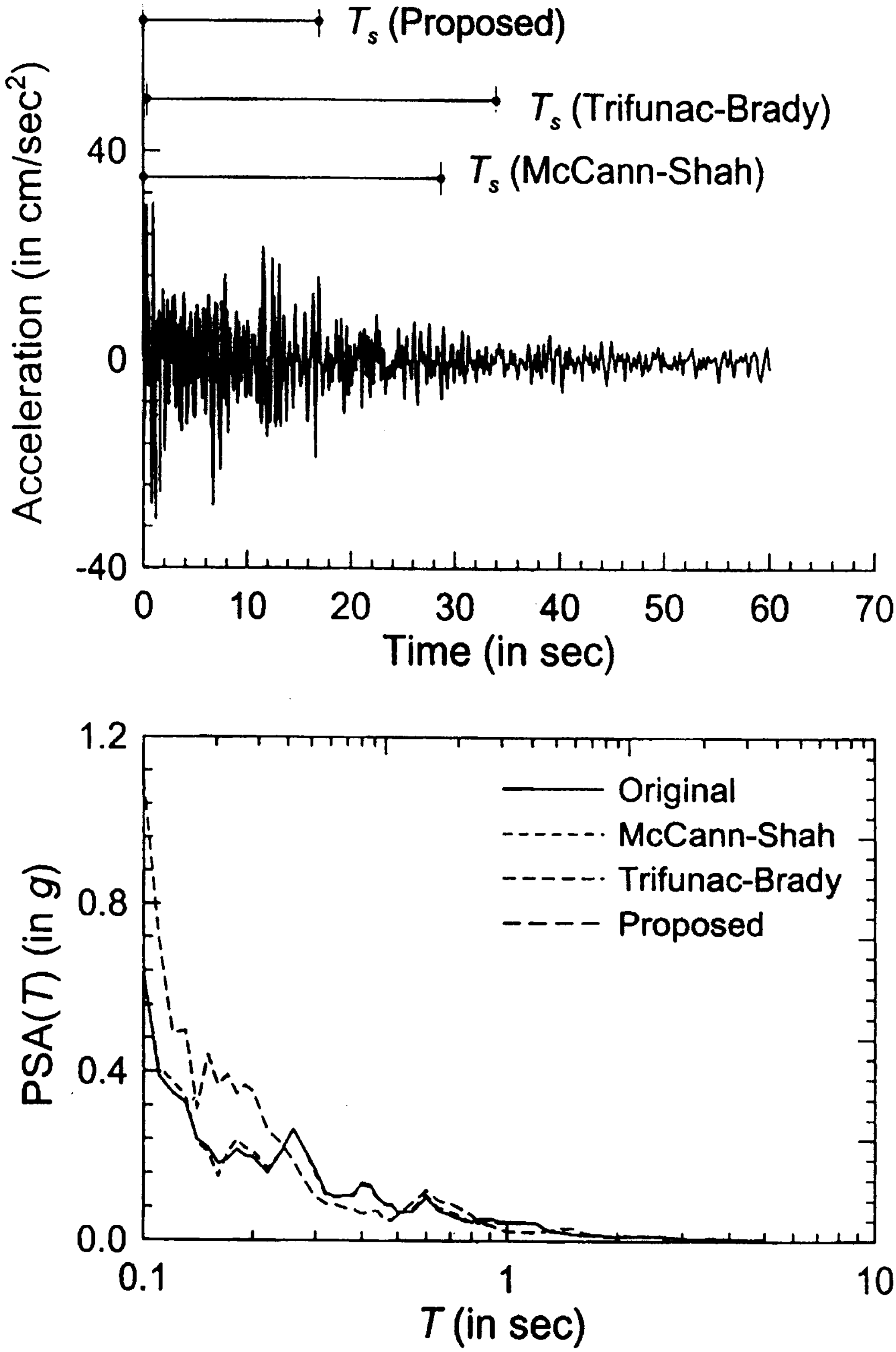


Figure 3 -Comparison of Strong Motion Segments and Corresponding Non-linear PSA Spectra for (Recently) Proposed, Trifunac-Brady and McCann-Shah Definitions in Case of Imperial Valley Motion.

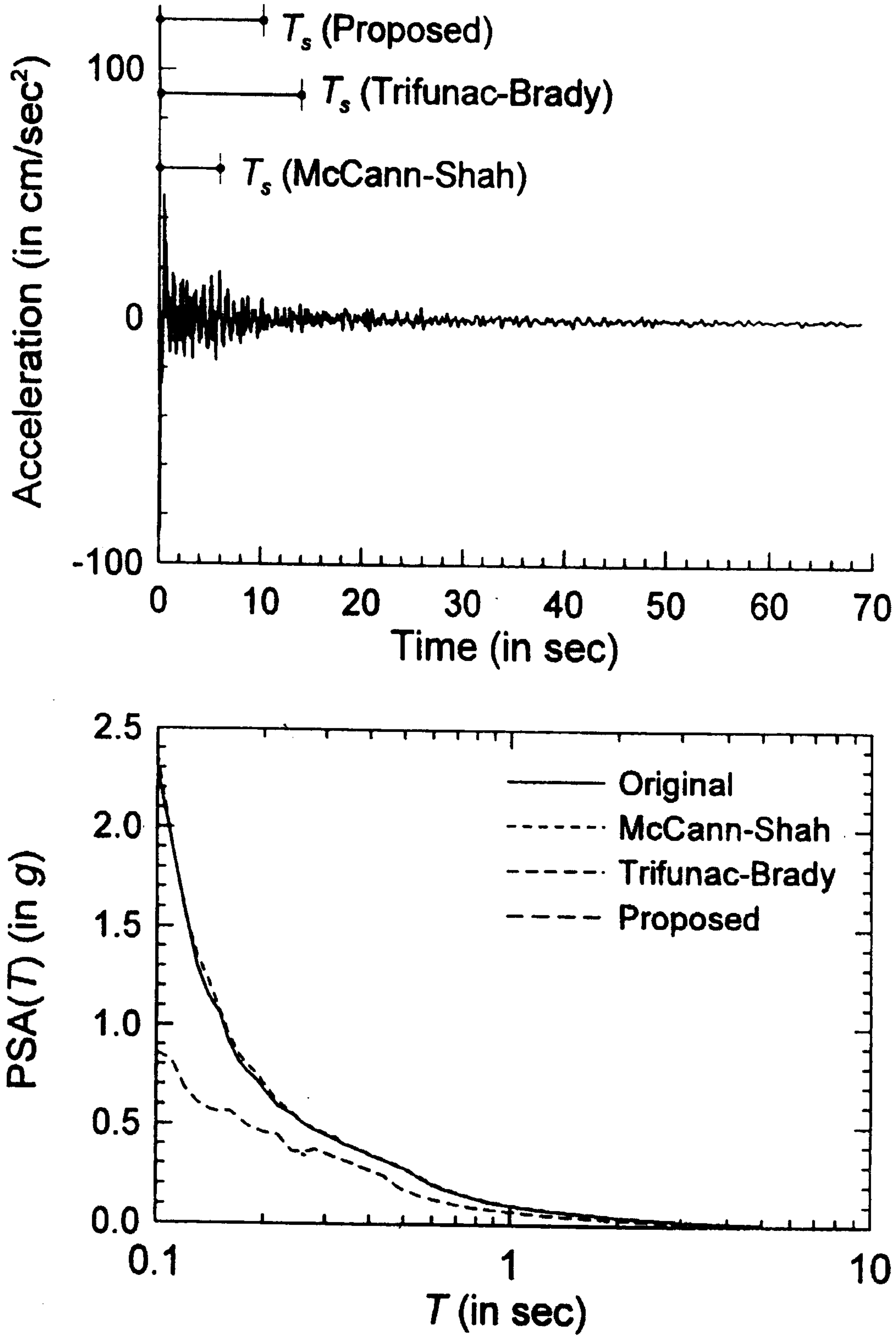


Figure 4 -Comparison of Strong Motion Segments and Corresponding Non-linear PSA Spectra for (Recently) Proposed, Trifunac-Brady and McCann-Shah Definitions in Case of Southern California Motion.

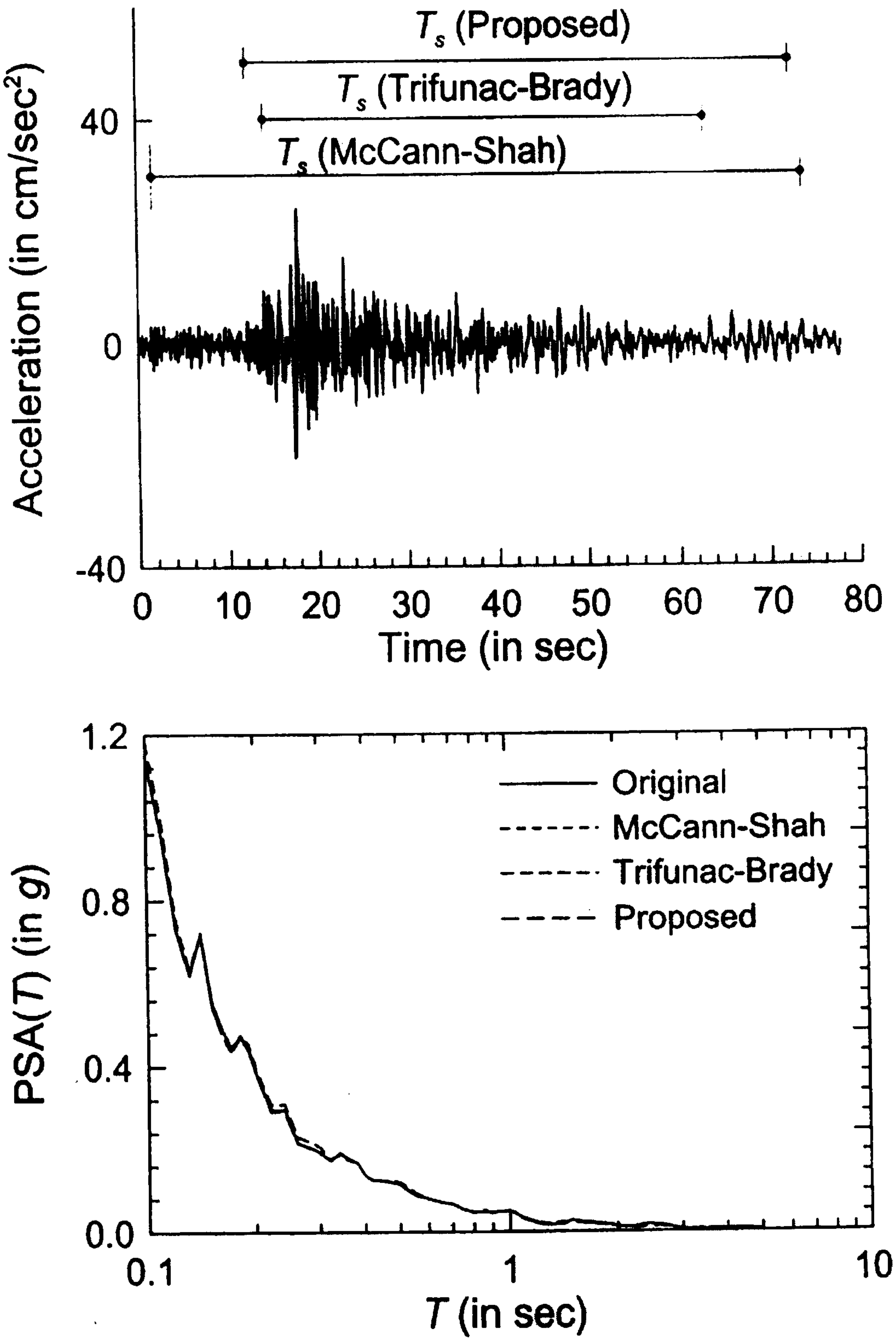


Figure 5 -Comparison of Strong Motion Segments and Corresponding Non-linear PSA Spectra for (Recently) Proposed, Trifunac-Brady and McCann-Shah Definitions in Case of Lower California Motion.

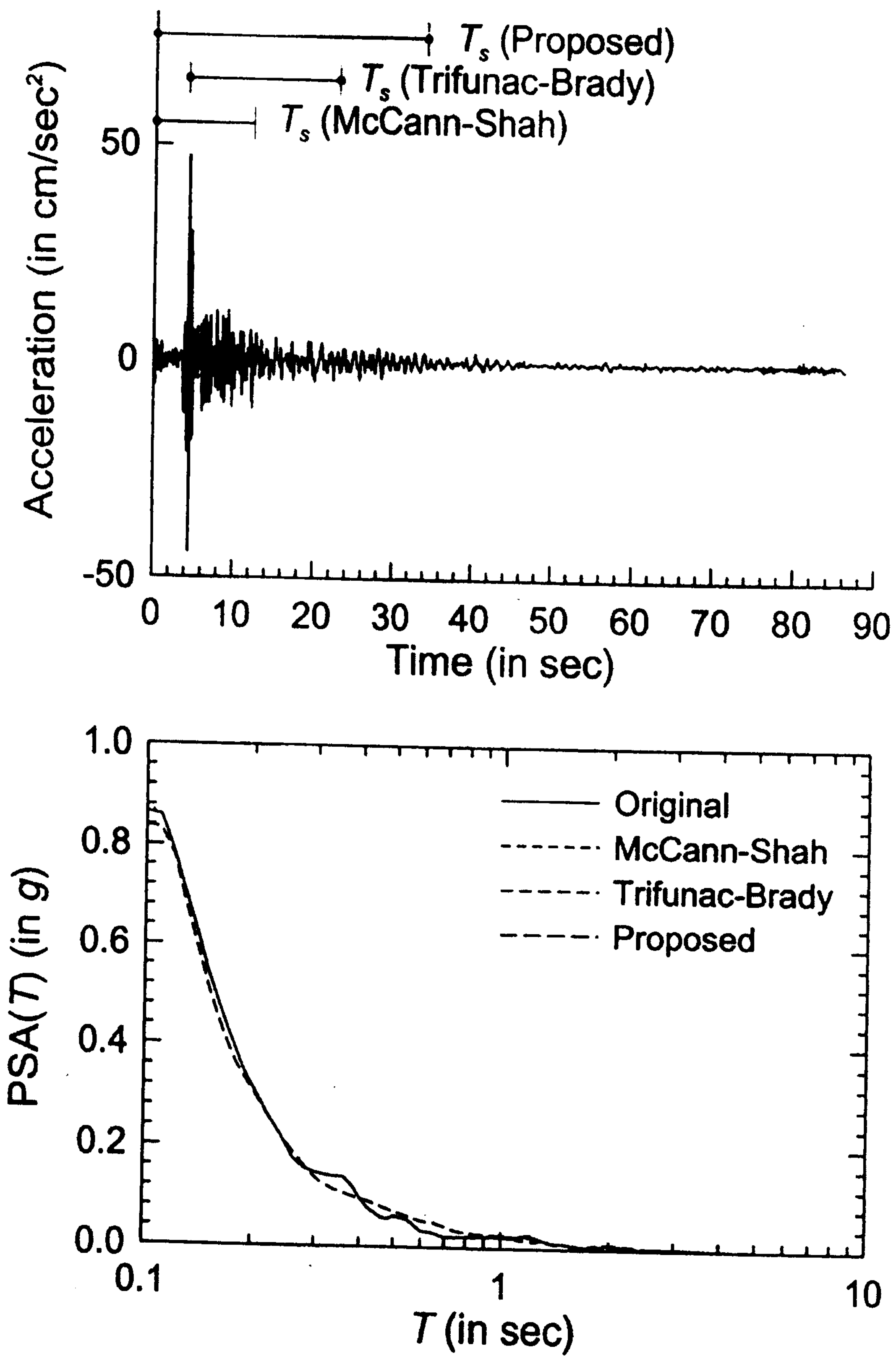


Figure 6 -Comparison of Strong Motion Segments and Corresponding Non-linear PSA Spectra for (Recently) Proposed, Trifunac-Brady and McCann-Shah Definitions in Case of Northern California Motion.

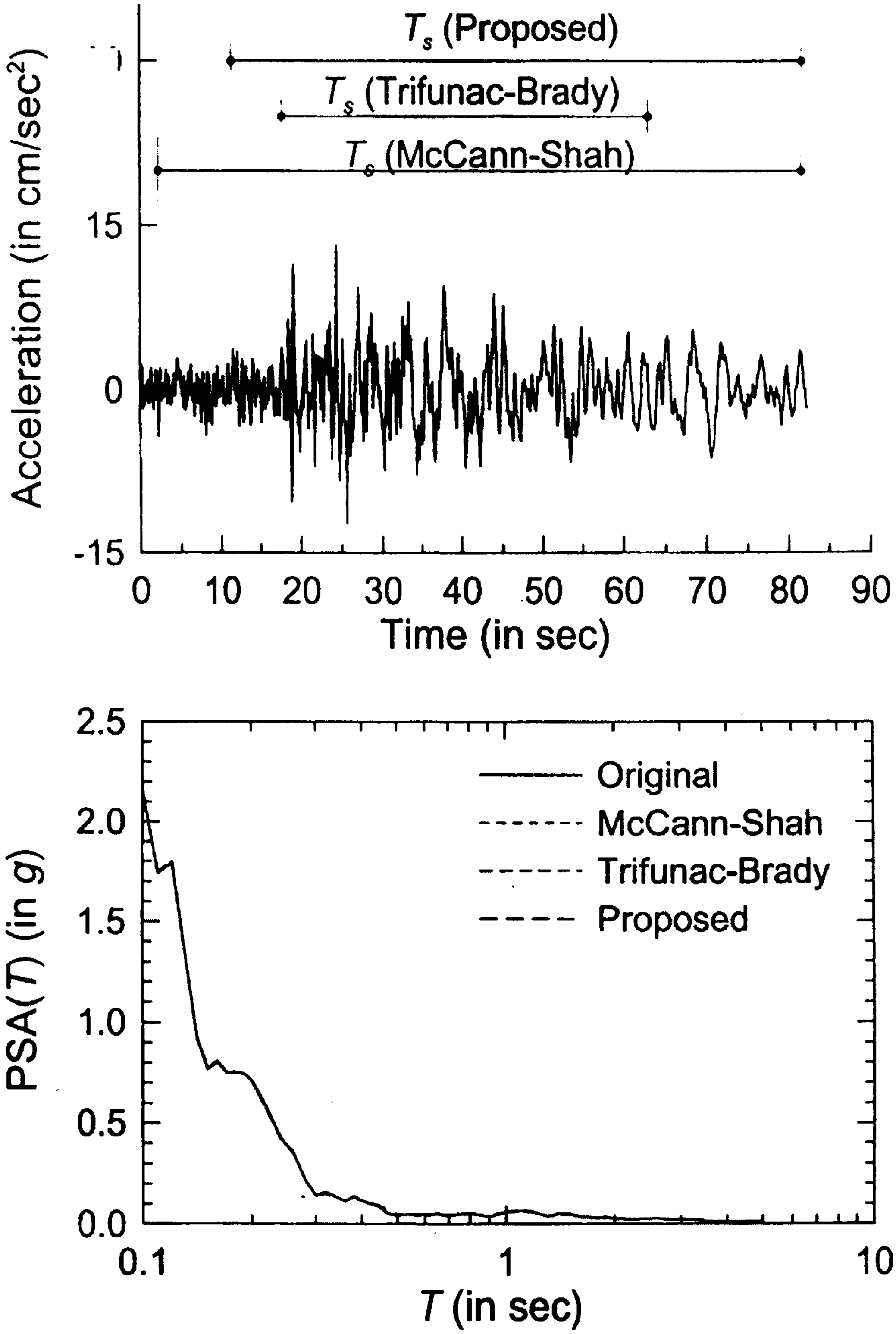
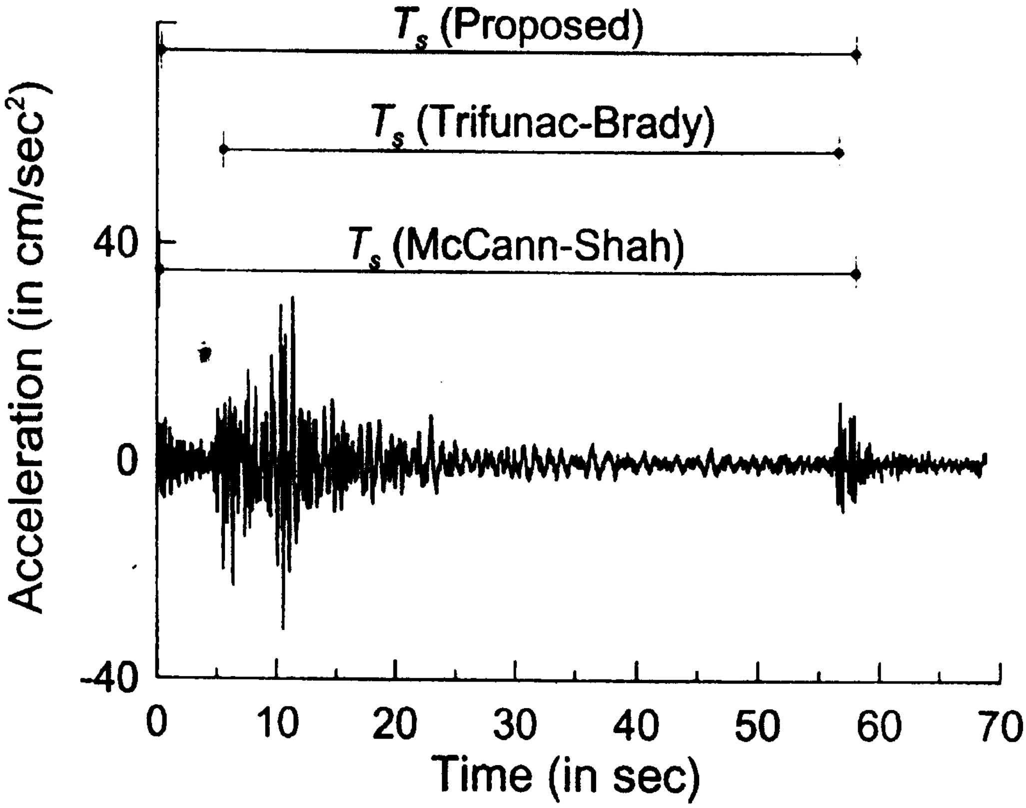


Figure 7 -Comparison of Strong Motion Segments and Corresponding Non-linear PSA Spectra for (Recently) Proposed, Trifunac-Brady and McCann-Shah Definitions in Case of Borrego Mountain Motion.



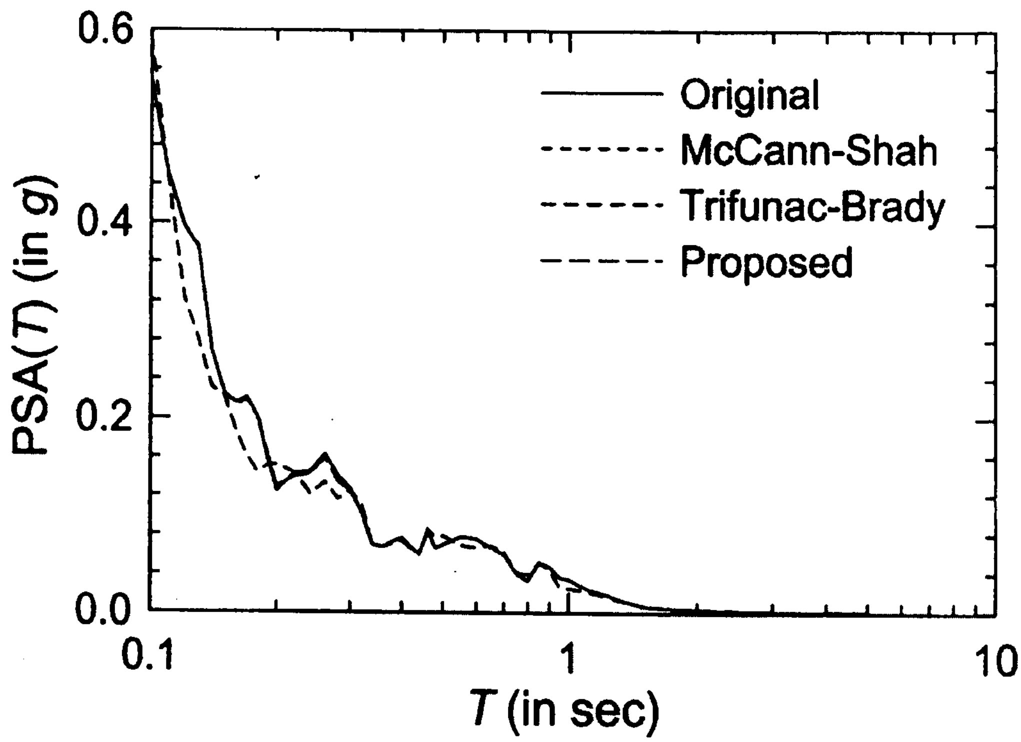


Figure 8 -Comparison of Strong Motion Segments and Corresponding Non-linear PSA Spectra for (Recently) Proposed, Trifunac-Brady and McCann-Shah Definitions in Case of Livermore Motion.