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Paper No. 209. (quote when citing this article)
Eleventh World Conference on Earthquake Engineering
ISBN: 0 08 042822 3

ANALYSIS OF SEISMIC RECORDS FROM THE WILDLIFE LIQUEFACTION SITE

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ABSTRACT

During the 1987 Superstition Hills earthquake, the strong motion data were recorded at the Wildlife Site, Imperial Valley, California at the ground surface and 7.5 m downhole, while seismically induced pore water pressures were recorded at several depths. This paper provides yet another analysis and interpretation of this important case study, focusing this time on the: (i) recorded manifestation of volumetric threshold cyclic shear strain, defined as the cyclic shear strain below which residual (permanent) pore water pressures do not develop and above which they developed rapidly, (ii) effects of the tendency towards lateral expansion followed by lateral spreading and cracking, which is believed to have affected the pore water pressure development by slowing down its buildup and causing distinctive spikes in ground surface accelerograms, and (iii) slow buildup of residual pore water pressures even after the ground surface accelerations have become very small.

KEY WORDS

Acceleration; Field Measurements; Liquefaction; Case History; Pore Water Pressures; Site Response.

INTRODUCTION

The liquefaction of the Wildlife site in the Imperial Valley, California, in 1987 (M_s = 6.6 Superstition Hills earthquake) is the best recorded liquefaction case history. The key elements of the instrumentation and post-earthquake observations are shown in Figs. 1 and 2, while the most relevant time histories are shown in Fig. 3. As indicated in Figure 3, the earthquake caused the recorded excess pore water pressures, u, to rise to the level corresponding to full liquefaction, and even higher. This was manifested on site by sand boils, cracking of the ground surface and lateral displacements. In Fig. 1 it is indicated that most of the sand boiling occurred above and around the instrumentation and was concentrated along a couple of major cracks. Other secondary cracks, further away from the instrumented site, developed parallel to the Alamo River. Lateral movements and spreading above the instruments occurred predominantly in the north-east direction perpendicular to the major ground cracking (Youd and Bartlett, 1988).

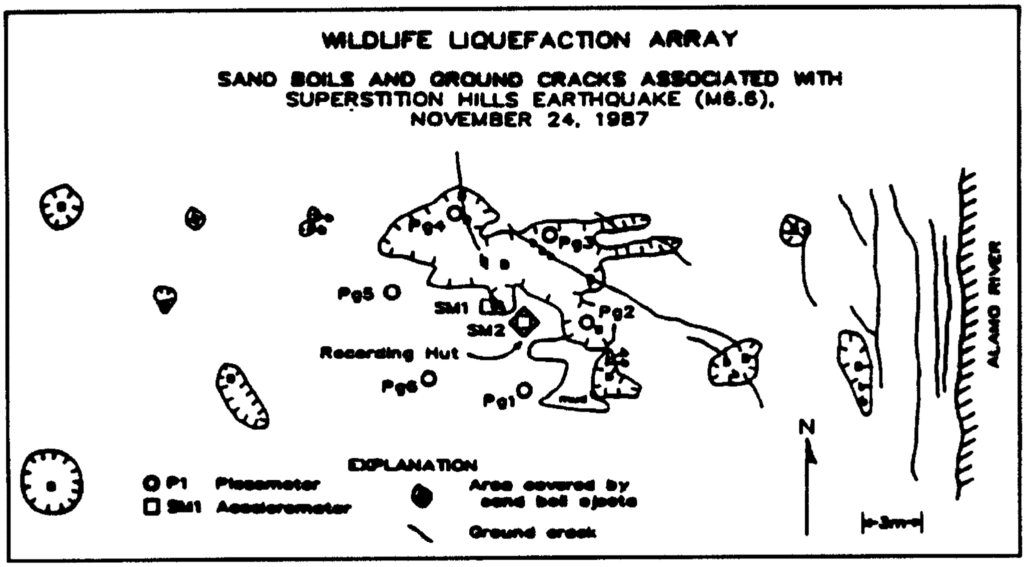
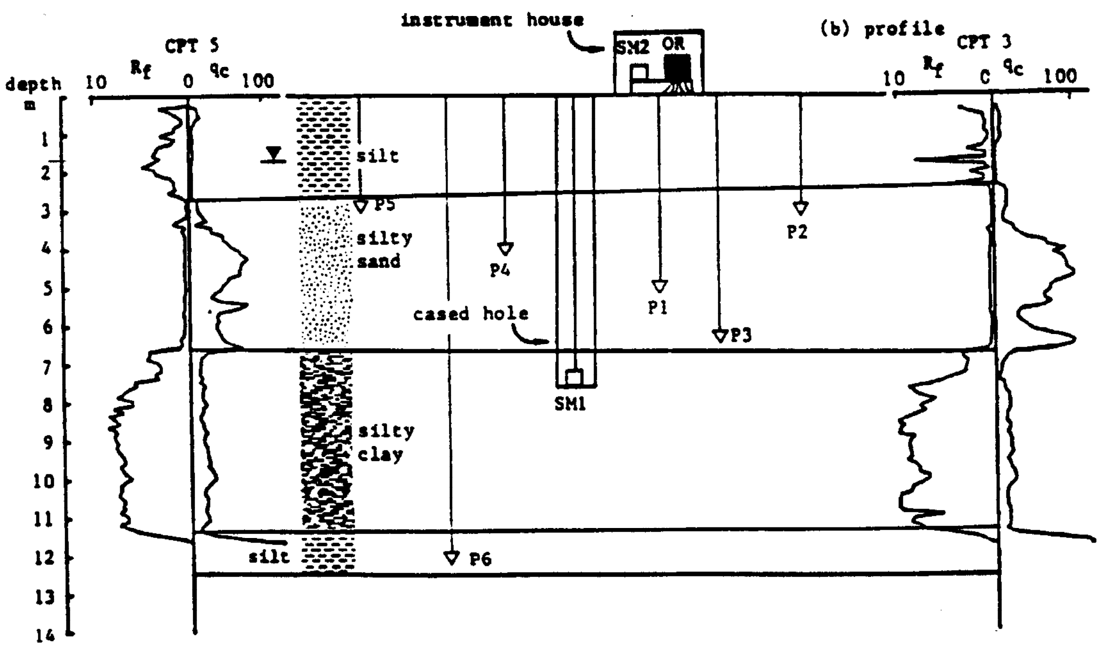


Fig. 1. Location map of the Wildlife Site and the 1987 Superstition Hills earthquake effects (Holzer *et al.*, 1988)



SM1 = downhole accelerogram
SM2 = ground surface accelerogram
P1 to P6 = piezometers for recording of pore water pressures

Fig. 2. Instrumentation of the Wildlife Site (Bennett *et al.*, 1984)

Numerous investigators have studied this truly unique liquefaction case history (e.g., Holzer *et al.*, 1989; Dobry *et al.*, 1989; Zeghal and Elgamal, 1994; Zorapapel and Vucetic, 1994). In this paper, three of its aspects that have not been examined previously to a satisfactory extent, are discussed. These are: (i) manifestation of volumetric threshold cyclic shear strain, γ_{tv} , defined as a cyclic shear strain below which residual (permanent) excess pore water pressures do not develop and above which they develop rapidly, (ii) effect of the observed tendency towards lateral expansion followed by lateral spreading and cracking which may have been responsible for the slowdown of the pore water pressures buildup, and (iii) continuation of the pore water pressure rise even after the ground surface accelerations have dropped to very small values. More details about these three and other aspects of the Wildlife Site seismic response can be found in the original report (Matasovic and Vucetic, 1993).

the major crack (see Fig. 1). INTERVAL 3: 18 to 28 sec. In this interval, the average *u* increase at slower rate from those corresponding approximately to $u^* = 0.4$ to 0.8. At both, the ground surface and downhole, the accelerations substantially dropped by the end of this interval. The ground surface accelerogram during this interval starts to exhibit a very long period, while the downhole does not, and consequently the two accelerograms are very different. Also the ground surface record exhibits several high frequency spikes. As shown in Fig. 4, those spikes that are in the negative direction, coincide with transient pore water pressure drops in the shallow piezometer P5 (and partly P2 as shown in Fig. 3). Holzer *et al.* (1989) hypothesized that this coincidence between the acceleration spikes and pore water pressure drops is probably associated with the dynamics of the lateral spreading accompanied by cracking. INTERVAL 4: 28 to 48 sec. In this interval the deposit practically liquefies, although *u* still slowly continue to rise. The frequency content of the ground surface accelerogram is noticeably lower than that of the downhole accelerogram, and the accelerations generally decrease to very small values. INTERVAL 5: 48 to 68 sec. In this interval the accelerations became extremely small while shaking has been ceasing. However, the pore water pressure buildup still slowly continues and practically stops at the end of the interval.

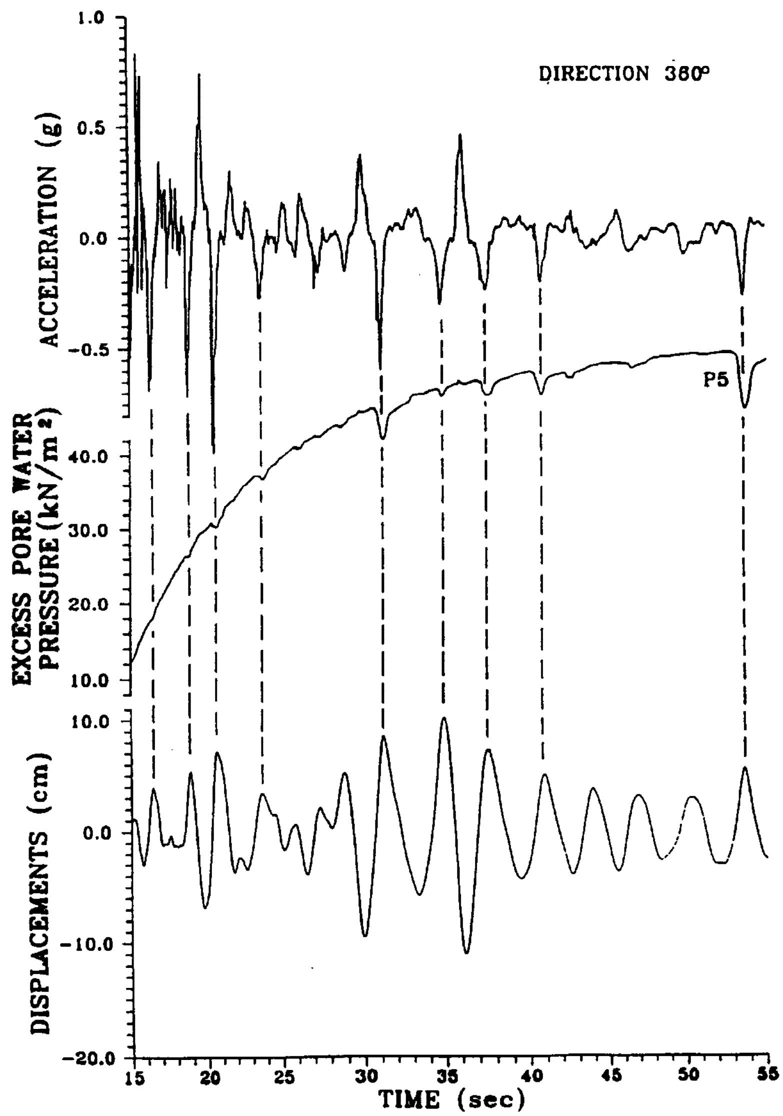


Fig. 4. Relation between the ground surface accelerations, pore water pressures and relative displacements in 360° direction (the displacements are obtained by double integration of accelerations) (Matasovic, J. and Vucetic, 1993)

ANALYSIS OF THE RECORDED DATA

The most relevant acceleration-time and earthquake-induced pore water pressure-time histories are plotted in Fig. 3. A careful comparison of these time histories indicates that, according to Zorapapel and Vucetic (1994), they can be divided into the following five distinct time intervals.

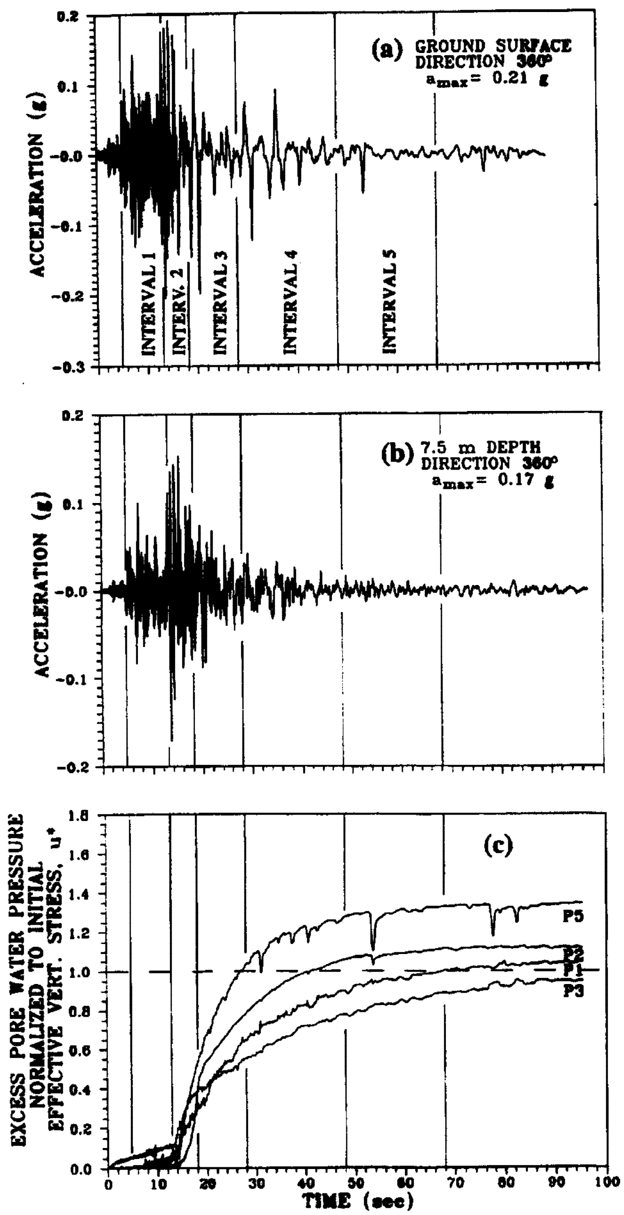


Fig. 3. Acceleration-time and pore water pressure-tim ehistories recorded during the 1987 Superstition Hills Earthquake (Matasovic, J. and Vucetic, 1993)

INTERVAL 1: 4.7 to 12.9 sec. 4.7 seconds correspond approximately to the arrival of the shear waves and the beginning of the buildup of small permanent pore water pressures, u, in the piezometers P1, P2 and P5. This should correspond to the beginning of the cyclic shear strains slightly larger than γ_{tv} . At 12.9 seconds a sudden increase of u starts. This time should correspond to the cyclic shear strains significantly exceeding γ_{tv} . Both ground surface and downhole accelerograms have a similar high frequency content.
INTERVAL 2: 12.9 to 18.0 sec. In this interval u builds up sharply, corresponding to $u^* = u/\sigma'_{vc}$ of 0.3 to 0.5, where σ'_{vc} = initial effective vertical stress. This is the strongest part of shaking, which starts with the strongest acceleration pulse of the record (0.21g at the ground surface and 0.17g at 7.5m depth), followed by several almost equally strong pulses. Towards the end of the interval, the frequency of motions recorded at the ground surface decreases, compared to the motions recorded at the 7.5m depth, suggesting that the degradation of soil stiffness occurred between the two accelerometers. It should be noticed that u builds up rapidly until the end of this stage, while afterwards during the next interval the buildup slows down. This is especially evident from the pore water pressure records P2 and P3 obtained around

As already noted, Fig. 4 exhibits an interesting coincidence between the acceleration spikes and sudden drops of u recorded by the piezometer P5 for the time window between 15 and 55 sec. The figure also includes associated displacement time history. It can be seen that the series of sharp acceleration spikes in one direction, the series of sudden drops in excess pore water pressures, and the peak displacements in one direction, coincide. It should be noticed that such behavior starts at the beginning of the Interval 3 after substantial pore water pressures have rapidly built up (at approximately 18 seconds), i.e., at the time when the rate of the buildup of u suddenly dropped.

Another important time history that should be compared to the development of u is that of the relative displacement vectors in the horizontal plane between 7.5 m depth and ground surface. The magnitude of the relative displacement vectors is obtained by subtracting the horizontal displacement vectors at 7.5 m depth from those at the ground surface, obtained by the double integration of associated horizontal accelerograms. The time history of the relative displacement vectors from 0 to 20 seconds is presented in Fig. 5, along with the dashed line corresponding to the γ_{tv}=0.017% of the Wildlife Site sand as determined by Vucetic and Dobry (1988).

A POSSIBLE SCENARIO OF THE LIQUEFACTION FAILURE

The abundance of data from the analyses of the Wildlife Site liquefaction by many other researches, along with the analysis described in this paper, enables a reconstruction of one possible scenario that led to the rise in pore water pressures, onset of liquefaction, and the behavior of the soil deposit afterwards during ground surface cracking and lateral spreading.

According to Fig. 5, during the first 5 seconds before the beginning of the Interval 1, the cyclic shear strains were below the volumetric threshold shear strain, γ_{tv} , and thus the low level of shaking could not cause any significant change of soil microstructure and buildup of u, except in P3 which can not be explained. At around 5 seconds, γ_{tv} started to be exceeded just slightly, and consequently small u started to build up. However, only after around 13 to 14 seconds at the beginning of Interval 2, the cyclic shear strains substantially larger than γ_{tv} were generated and u started to build up fast. At this time, the major earthquake shock has arrived, and during just a few cycles of shaking during Interval 2, the pore water pressure built up to about 30 to 60 percent of σ'_{vc}. According to the time of the appearance of acceleration spikes and transient drops of u in Figs. 3 and 4, it seems that after 18 seconds, at the beginning of Interval 3, the pore water pressures had built up high enough to soften the liquefiable layers to the point that the ground cracking and lateral spreading started.

The effect of cracking and lateral spreading on the acceleration and pore water pressure records is probably the most interesting aspect of this unique case study. It is reasonable to assume that a tendency of soil mass towards spreading precedes the development of cracks, and that the same tendency continues to be present during the cracking and lateral spreading. If this is true, this tendency towards the increase in volume must cause a slowdown in the rise of u. As emphasized above, at approximately 18 seconds, at the beginning of Interval 3, the rate of the buildup of u significantly decreased. Such a sudden change in the rate of the buildup of u therefore coincides with the beginning of episodic cracking and lateral spreading. Accordingly, it is suggested here that the fundamental component of the process of cracking, spreading and subsequent large lateral movements is lateral expansion of the soil mass or, in an undrained condition, a tendency towards lateral expansion, which consequently slows down the buildup of u. The coincidence of acceleration spikes and transient drops of u can be explained by the same concept. A pore water pressure drop is caused by a sudden opening of a crack which simultaneously increases the effective stresses in the soil and thus the soil stiffness and strength. During such a temporary gain in strength, the soil is able for a very short period of time to transmit larger stresses which is manifested by a spike in the ground surface accelerogram. As a part of the same process, the cycles of acceleration spikes must coincide with large displacements in the general direction of the spreading.

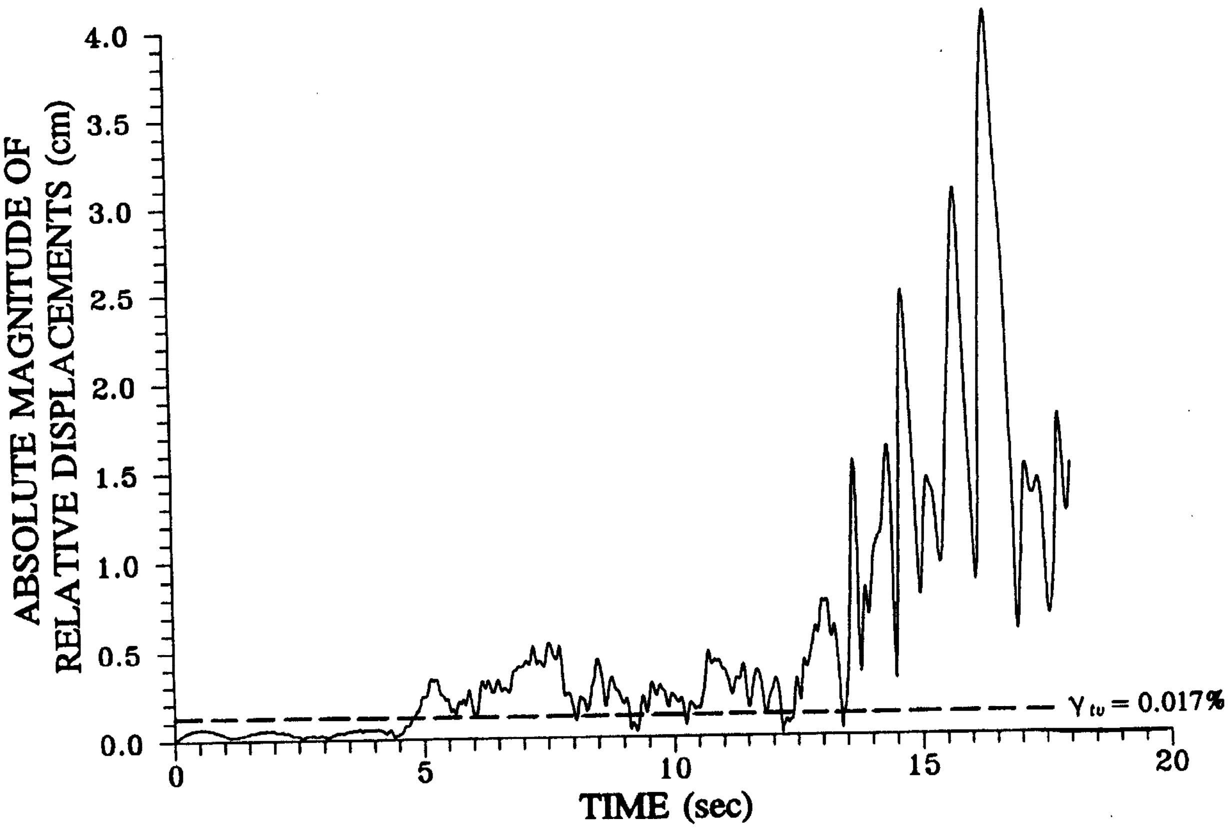


Fig. 5. **1987 Superstition Hills earthquake - Relative displacements in the horizontal plane (0 to 18 seconds) versus time (Matasovic, J. and** Vucetic, 1993)

In other words, from the beginning of a tendency towards lateral spreading, and during the spreading thereafter, two parallel excess pore water pressure generation mechanisms were continuously present in the Wildlife Site soil mass. The first one was the pore water pressure increase due to the ground shaking and consequent tendency of the saturated soil to densify, which dominated the buildup of u. The second was the pore water pressure decrease caused by the lateral expansion or its tendency. The net effect was therefore, as shown by the pore pressure records, a slowed-down pore pressure buildup starting at approximately 18 seconds. These two mechanisms and their cumulative effect are sketched in Fig. 6. Without the superposition of "negative" pore water pressures caused by lateral spreading, u would most likely continue to build up at the rate similar to that recorded between 13 and 18 seconds. The nonlinear site response analysis by Thilakaratne and Vucetic (1990) tends to confirm that.

In the middle and towards the end of the event, after 28 seconds during Intervals 4 and 5 and after, accelerations were decreasing and became very small except for several spikes, while the pore water pressures were still slowly rising. Such interesting relation between the pore water pressures and accelerations is the result of the almost full softening of the liquefiable soil layer, or a part of it. As explained by Thilakaratne and Vucetic (1989), due to such softening the layer cannot successfully transmit upward-propagating ground motions because they are absorbed by large deformations. At the same time, however, soil below may still be subjected to incoming shaking and cyclic shearing that generates pore water pressures. This suggests that the ground surface accelerograms cannot be used directly to predict the buildup of seismic pore water pressures.

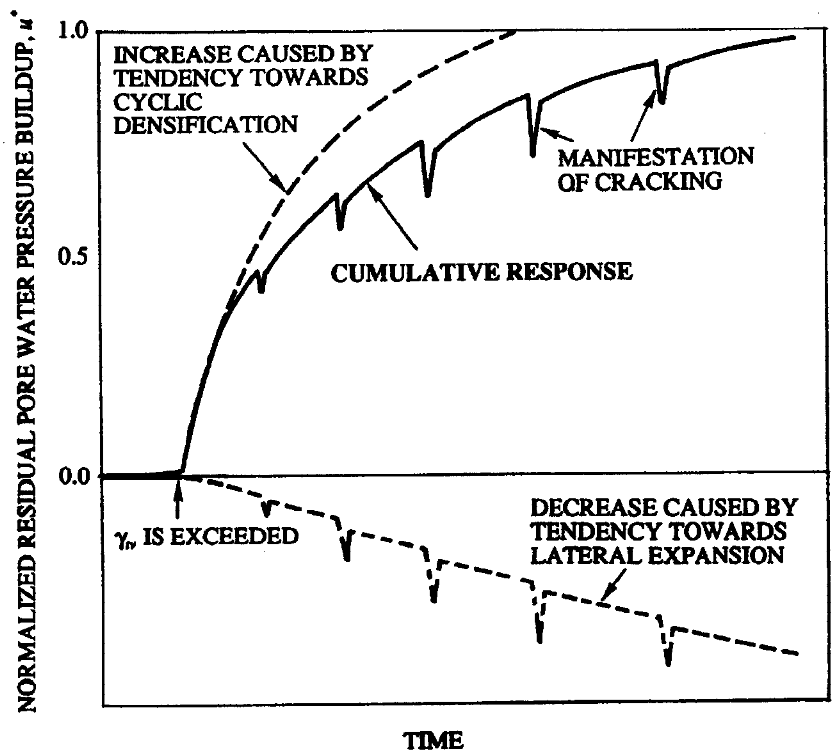


Fig. 6. Mechanism of seismic residual pore water pressure buildup at slightly inclined ground

SUMMARY AND CONCLUSIONS

Liquefaction of soils is a complex 3-dimensional phenomenon that is still not completely understood. Therefore, case studies such as the Wildlife Site are of extreme importance for understanding of liquefaction phenomenon and should be studied in the greatest detail. The study summarized here represents such an attempt.

In this paper, special attention is paid to some aspects of the mutual comparison of recorded accelerations, relative displacements, excess pore water pressures and occurrence of ground cracking and lateral spreading. Based on the collected evidence and its analysis, it can be concluded that: (i) an appropriate way to analyze the mechanism of seismic pore water pressure buildup, liquefaction and associated surface manifestations is to consider cyclic shear strain as the governing parameter, in particular the volumetric threshold cyclic shear strain; (ii) cyclic shear strains, seismic pore water pressures, and ground surface accelerations are intimately related in a very logical way; (iii) a tendency towards lateral expansion followed by lateral spreading and cracking may significantly affect the pore water pressures by slowing down their buildup, as well as by causing distinctive spikes in ground surface accelerograms; and (iv) a significant softening of a layer of soil deposit can cause a drop in the ground surface accelerations, while at the same time the pore water pressure may keep slowly increasing due to continued cyclic shear straining of the softened zone caused by the shaking below it.

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