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An Experimental Study on Dynamic Responses of Geo-Materials during Fracturing

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Abstract

The dynamic behaviour of rocks during the failure process is not being investigated so far, although it has very important implications on the failure response of rock engineering structures as well as ground motions induced by earthquakes. The author performed some experiments under different loading environment with testing machines of three different institutes on various types geo-materials in order to enhance our knowledge and understanding on the dynamic behaviour of rocks during fracturing. Following some brief information on the testing machines and testing procedures, the experimental results are presented according to each testing environment and their implications are discussed.

1. INTRODUCTION

The dynamic responses of geo-materials during fracturing have not received any attention in the fields of geo-engineering and geo-science. However, these responses may be very important in the failure phenomenon of geo-engineering structures (i.e. rockburst, squeezing, sliding) and the ground motions induced by earthquakes. For example, the estimation of the travel distance and path of rock fragments during rockbursts in underground excavations is very important for assessing the safety of workmen and equipments. It is also known that the ground motions induced by earthquakes could be higher in the hanging-wall block or moving side of the causative fault as observed in the 1999 Kocaeli earthquake (Aydan et al. 2000) and the 1999 Chi-chi earthquake (Tsai & Huang, 2000).

The recent advances in measurement, monitoring and logging technologies enable us to measure and monitor the dynamic responses of geo-materials during fracturing. Therefore, the studies concerning the dynamic responses of geomaterials during fracturing can now be easily undertaken as compared with that in the past. The author has been carrying out such a study in recent years. The experiments have been performed on geo-materials ranging from very soft materials such as clay to hard rocks such as silicious sandstone by using different loading schemes and loading frames, which may be quite relevant particularly in the actual situations in geo-engineering and geo-science. This article describes these experiments and experimental results concerned with the dynamic responses of geo-materials during fracturing and discuss their implications in geo-engineering and geo-science.

2. EXPERIMENTAL SET-UPS AND MATERIALS

The experiments have been carried out at the rock mechanics laboratories of three institutes, namely, Tokai University (TU), Ryukyu University (RU) in Japan and Middle East Technical University (METU) in Turkey. Although the loading frames used in Tokai University has a low capacity, they are easily operated so that a great number of experiments could be performed. The fundamental characteristics of the loading devices are illustrated in Figure 1(a,b) and Figure 2(a,b). The loading devices at RU and METU are of high capacity as shown in Figure 2(c,d). While the loading machine of the RU produced by SHIMADZU of Japan is of low-stiffness with a loading capacity of 2000 kN, the testing machine of METU is a servo-control testing machine produced by MTS with a capacity of 1000 kN.

The loads imposed on and displacements of the samples tested in the TU are simultaneously measured through the utilization of laser displacement transducers while they are measured through load cells and contact

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type displacement transducers in the experiments at the RU and METU. In all experiments, the acceleration responses of the samples during fracturing were measured by Yokogawa WE7000 measurement station using the AR-10TF type accelerometers of TOKYO SOKKI, which can measure three component accelerations up to 10G with a frequency range of 0-160Hz. The accelerometers were either attached to samples directly or top and bottom platens. However, if the sample was large enough, the accelerometers were attached directly onto samples as seen in Figure 2(c). The accelerations were measured in the direction of loading and in two mutually perpendicular directions to the loading direction, one of which generally corresponds to the radial direction.

There is no doubt that the effect of stiffness of the top and bottom parts of the loading systems used in this study has some certain effect on the overall acceleration responses. However, the actual situations in geo-engineering and geo-science should be similar to the loading systems in laboratory as one part of the loading system mobilised during fracturing and this action is stabilised by the surrounding media under natural conditions. If the overall system is not stabilised, the consequences should be catastrophic, which is not the general case in nature.

3. EXPERIMENTS AND RESULTS

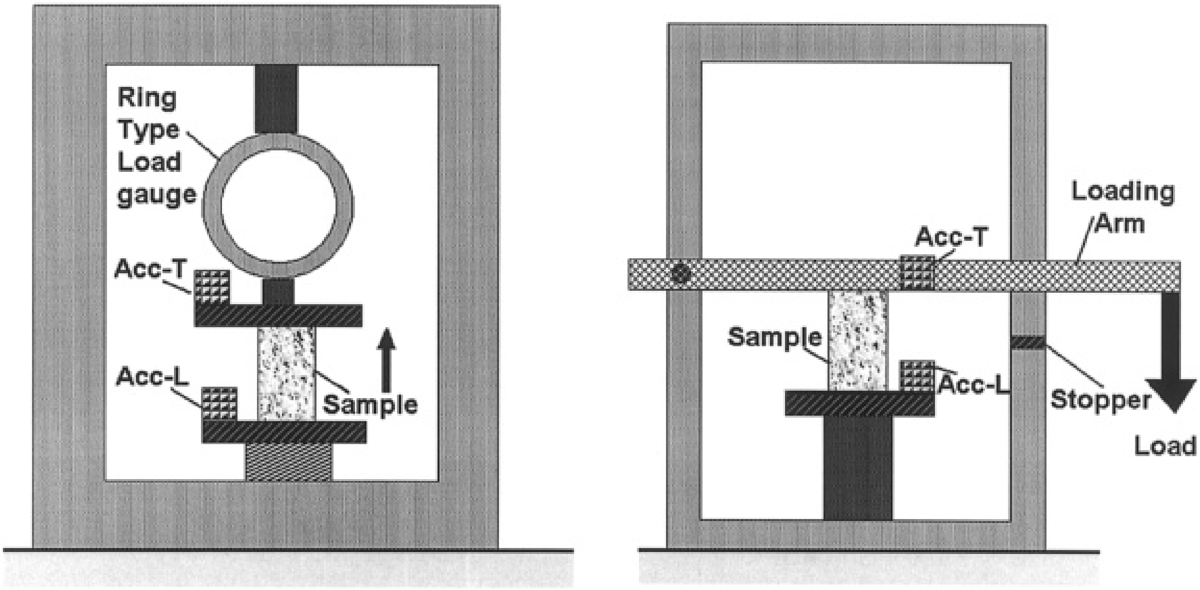
The experiments and the results obtained are described according to the institute where the experiments were carried out.

3.1 Tests at Tokai University

3.1.1 Tests Using Soil Mechanics Compression Testing Machine

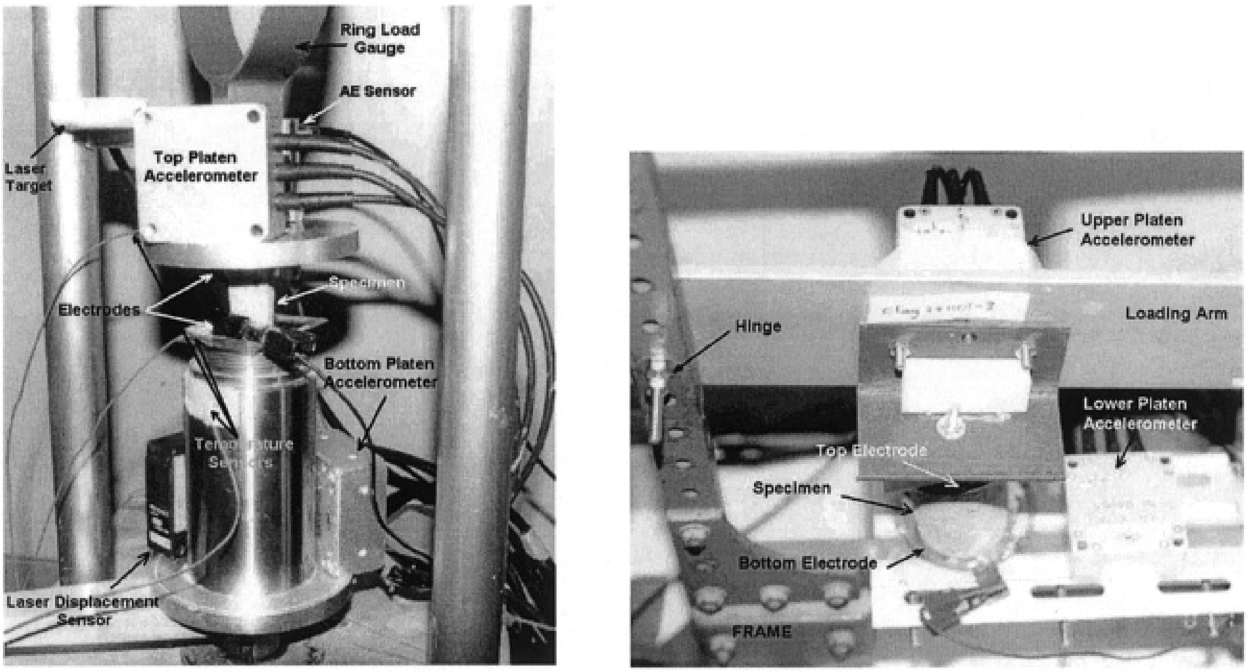
The experimental device is a low capacity and low stiffness testing machine. The load on the sample is measured through a ring type load gauge with a stiffness of 22.55 kgf/mm (Figure 1(a)). Figures 3 and 4 show the acceleration records during the failure process of tuff samples from Avanos and Ürgüp in Cappadocia region of Turkey. The uniaxial strength of samples was 248 kPa for Avanos sample (AV1-13-4) and 2480 kPa for Ürgüp sample (U1-3-h2). Since the stored energy of the ring load gauge for sample U1-3-h2 is greater than that for sample AV1-13-4, the amplitude of accelerations for sample U1-3-h2 is greater than that for sample AV1-13-4 during the release of the stored energy. It is also of great interest that the acceleration of the top platen is greater than that of the bottom platen. The amplitude ratio of maximum acceleration of the top platen to that of the bottom platen ranges between 1.16 and 1.54.

Figure 5 shows the acceleration response of Babadağ red marl (bkm-v3) during failure. In this particular example, the uniaxial strength of rock was about 8.23 MPa. Since the stored energy in the ring load gauge is much higher, the measured acceleration becomes larger. Furthermore, how the sample sheds its strength following the initiation of failure has also important effect on the amplitude of resulting acceleration responses. Figure 6 compares time-axial stress responses of samples mentioned above. Sample AV1-13-4 has a very low strength. Nevertheless, it behaves in a perfectly plastic manner for a certain amount of straining, while samples



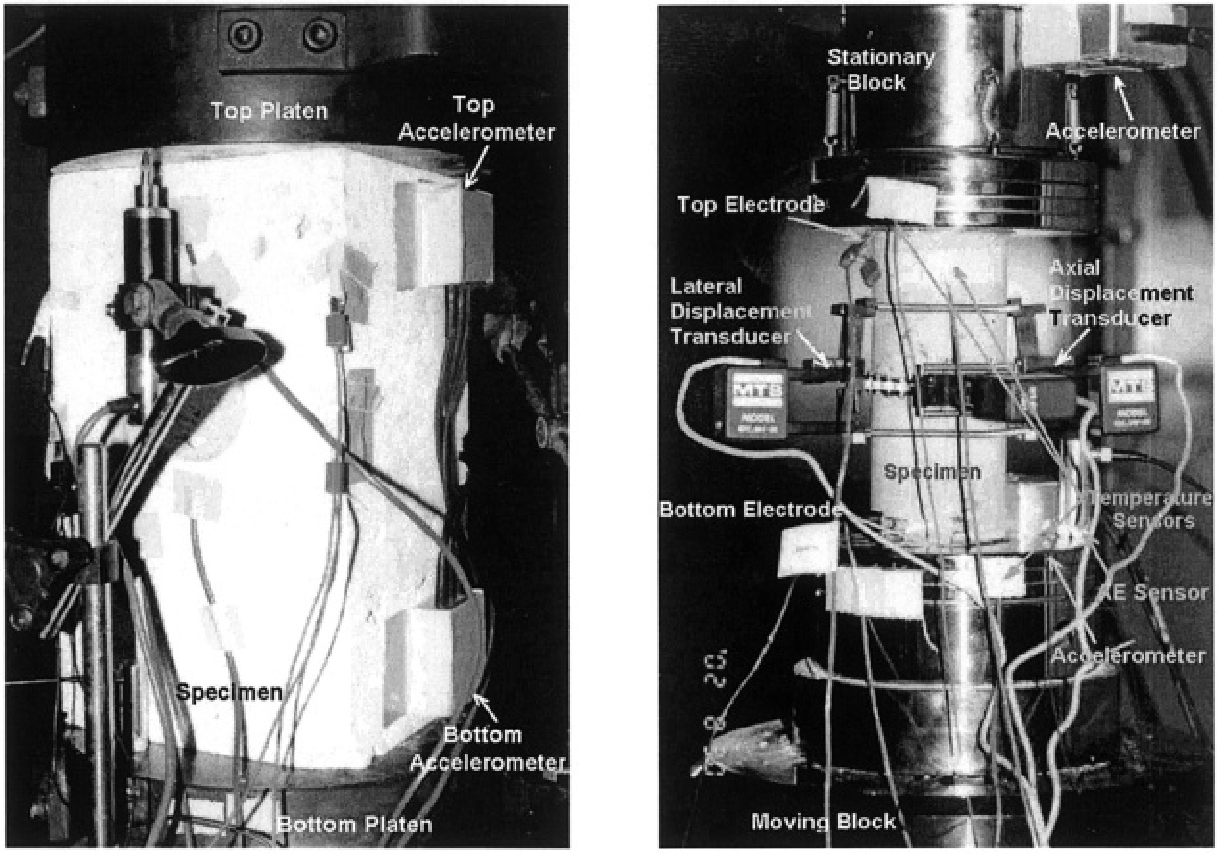
(a) Soil Mechanics Compression Testing Machine (b) Arm-type Creep Compression Testing Machine

Figure 1: Outline of the testing machines used in Tokai University tests



(a) Set-up 1 at Tokai University

(b) Set-up 2 at Tokai University



(c) Set-up at Ryukyu University

(d) Set-up at Middle East Technical University

Figure 2: Views of experimental set-ups used in laboratory tests

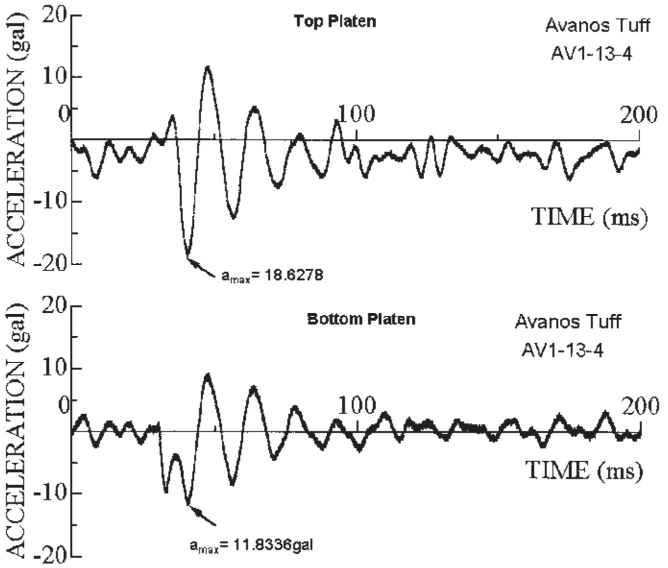


Figure 3: Axial acceleration response of sample AV1-13-4 during failure

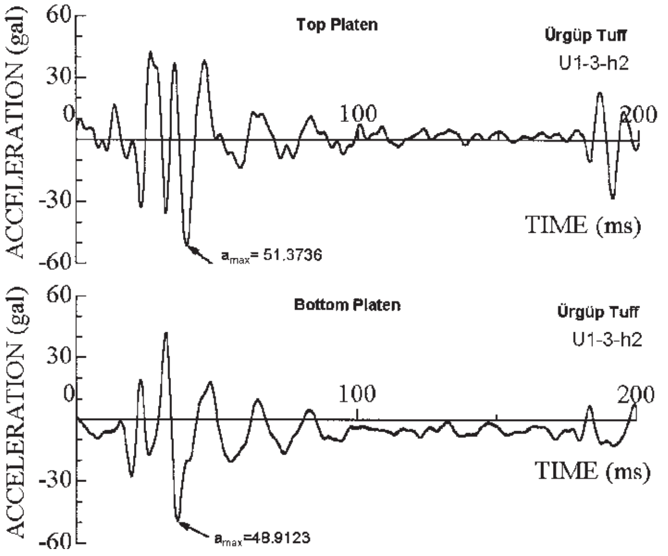


Figure 4: Axial acceleration response of sample U1-3-h2 during failure

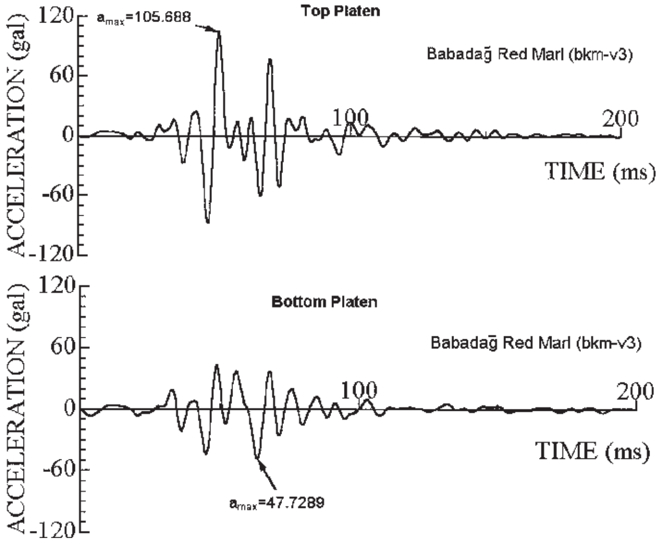


Figure 5: Axial acceleration response of sample bkm-3 during failure

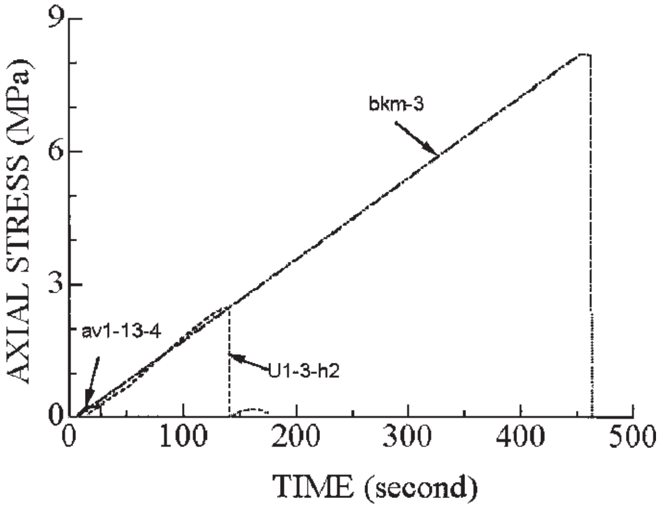


Figure 6: Comparison of axial stress-time responses of samples

U1-3-h2 and bkm-v3 loose their strength in a very brittle manner. These responses probably have some important implications on the squeezing and bursting behaviours of rocks observed during the failure of rock engineering structures.

3.1.2 Tests with Arm-type Creep Compression Testing Machine

A number of tests on different rock types were carried out by using the arm-type creep compression testing machine (Figure 1(b)). Because of the nature of the testing machine, the acceleration response is directly associated with the moment at the time of failure and the post-failure behaviour of samples. As specific examples, two experimental results are given herein. One sample is Kibushi clay and the other sample is Washuzan weathered granite. Figure 7 and 8 shows the measured acceleration responses during failure. Since the moment capacity of

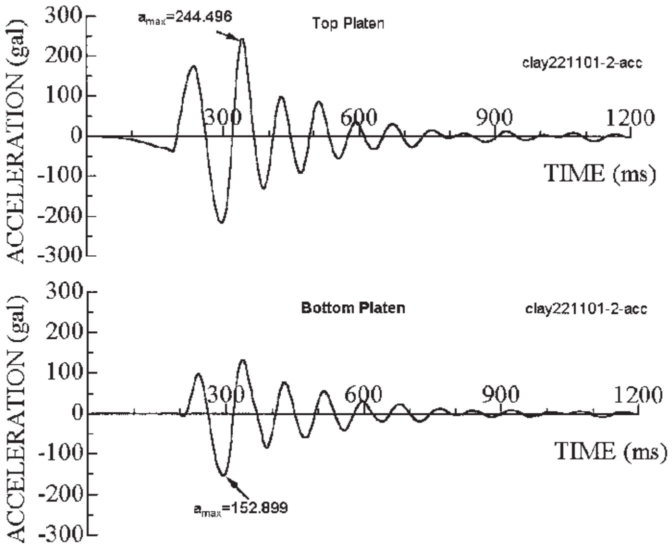


Figure 7: Axial acceleration response of sample clay221101-2-acc during failure

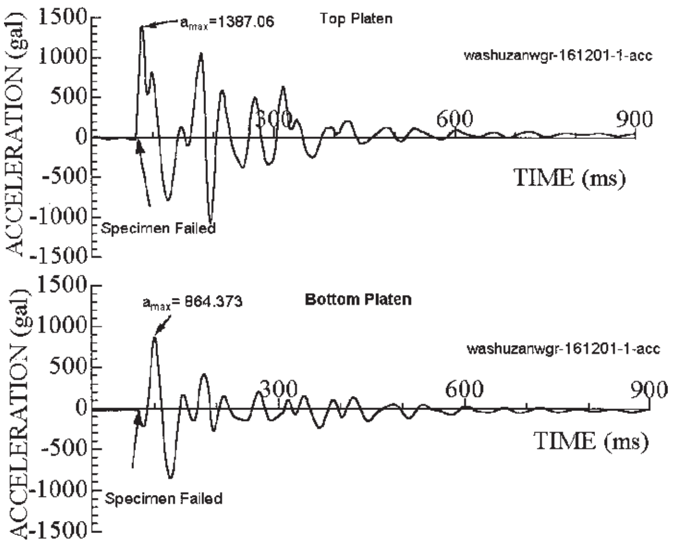


Figure 8: Axial acceleration response of sample washuzanwgr161201-1-acc during failure

clay sample clay-221101-2-acc was less than that for sample washuzanwgr-161201-1-acc, the acceleration amplitude of the clay sample is about 0.2 times that for weathered granite sample. In these two examples of acceleration responses, it is once again noted that the amplitude of acceleration of the top platen is higher than that of acceleration of the bottom platen and the amplitude ratio ranges between 1.48 and 1.61. In other words, the mobile part of the system after the failure is subjected to higher acceleration as compared with the stationary part of the system.

3.2 Tests at Ryukyu University

Tests on samples of Ryukyu limestone and sandstone of the third Shizuoka Tunnel of the second TOMEI highway were performed. Among these tests, three acceleration records of sample A1 during failure are presented in Figure 9 and the overall load, AE responses with time are shown in Figure 10. Fundamentally, the observed acceleration responses are similar to those of the previous examples except their absolute values. The most striking feature is the chaotic acceleration response during the initiation and propagation of the macroscopic fracture of the sample. This chaotic response is very remarkable for the radial acceleration component of the top platen in particular. Probably, this phase may be associated with the small fragment detachments before the final burst of rock samples. The small fragments result from splitting cracks aligned along the direction of loading before they coalesce into a large shear band. Furthermore, the audible sounds of fracturing are emitted from the rock during this phase.

3.3 Tests at Middle East Technical University (METU)

The samples of marl used in testing were gathered from Demirbilek open-pit lignite mine in Western Turkey. Since the testing machine was a servo-control testing machine, the rock deformation was strictly controlled and the violent failure phenomenon did not occur to trigger the accelerometers. However, one of the samples was accidentally subjected to a shock loading causing the failure of the sample during which accelerometers were triggerred. Figure 11 shows the acceleration response of the axial components of the moving and stationary blocks of the loading system. The amplitude ratio for this particular test is about 2.4. Once again, the moving part of the system experiences greater accelerations. Furthermore, the acceleration response of the moving part is not symmetric while the stationary part shows a symmetrical response. This feature resembles to those recorded in the recent great in-land earthquakes in Turkey and Taiwan.

4. CONCLUSIONS

The author presented the outcomes of an experimental study on the acceleration responses of geo-materials during fracturing. Tests were carried out under different loading environments and using different types of testing machines. In-spite of differences in loading environment and testing machines, the experimental results have some striking similarities, which may be summarised as follows:

a) The amplitude of accelerations of the mobile part of the loading system is higher than that of the stationary part. This feature has striking similarities with the strong motion records nearby earthquake faults observed in the recent large in-land earthquakes such as the 1999 Kocaeli earthquake of Turkey and the 1999 Chi-Chi earthquake of Taiwan. Furthermore, the wave forms of the acceleration records of the mobile part are not symmetric.

b) The amplitude of accelerations during the fracturing of hard rocks is higher than that during the fracturing of soft rocks. This is directly proportional to the energy stored in samples before the fracturing.

c) The chaotic responses in acceleration components perpendicular to the maximum loading direction may be observed. These may have some important implications for the procedures and interpretation of measurements for the short-term forecasting in geo-engineering and geo-science.

d) The post-failure behaviour of rocks also affects the acceleration amplitude and its wave form. If the failure is brittle, the induced accelerations can be quite high as compared with those failing in a ductile manner. This fact may have some important implications on whether rock behave as squeezing or

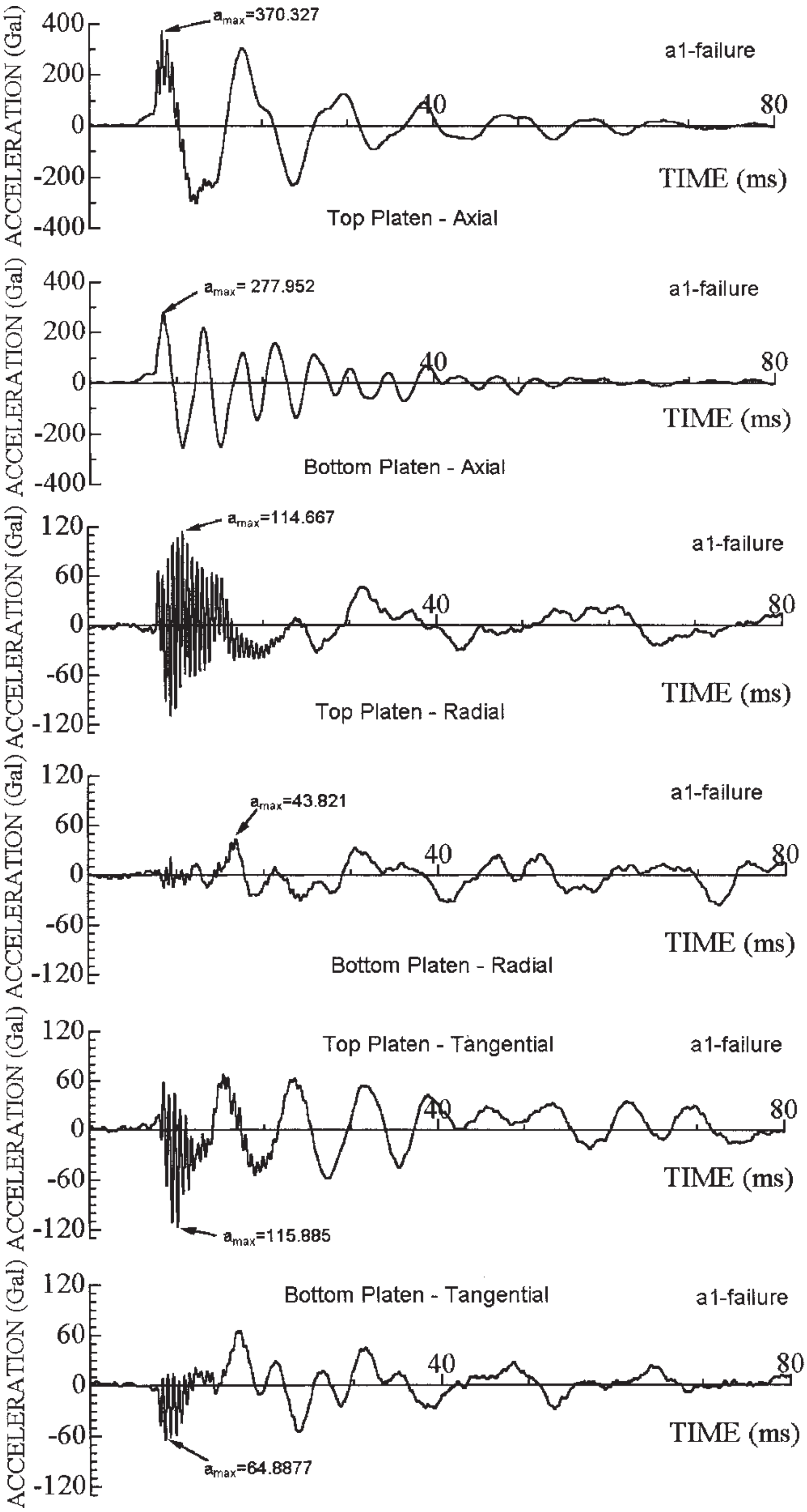


Figure 9: Acceleration records of three components on sandstone sample A1

bursting rock during the failure of rock engineering structures.

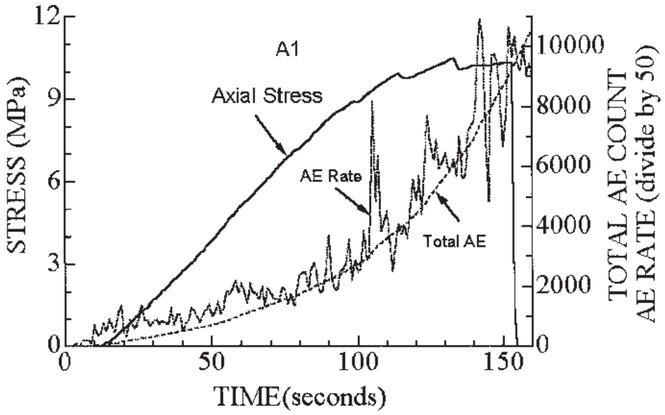


Figure 10: Axial stress and AE responses of sample A1

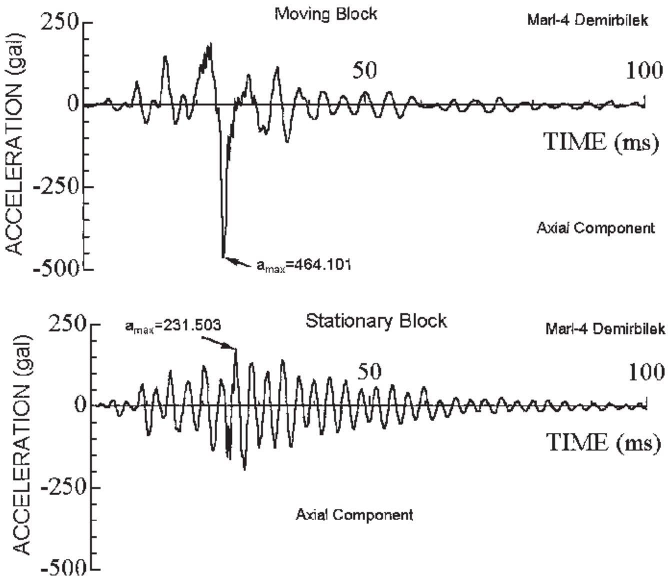


Figure 11: Acceleration responses measured during the shock-type loading on marl

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要　旨

地盤材料の破壊時における動的応答に関する実験的研究

アイダン・オメル
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岩盤構造物の破壊や地震に伴なう地盤の振動に対して重要であるにも係わらず岩盤の破壊時の動的挙動について研究例はほとんど見当たらない．著者は破壊時の地盤材料の動的挙動に対する理解と知識を深めるため異なる研究機関の試験機を用いて様々な地盤材料について室内試験を行った．本論文で，まず最初に実験に用いた各機関の試験機と試験方法を紹介している．そして，各機関の試験機を利用して行った破壊時における地盤材料の動的挙動に対する試験結果を説明し，その工学的および科学的意味あいについて論じている．得られた試験結果から試験装置の運動している側に接した供試体の加速度応答が静止している側のものに比べて大きくなることが明らかになった．このことは地震時に断層の運動する上盤で観測されている計測結果と類似し，実験的に観測結果を裏付けることができたと判断できる．また，実験結果は岩盤構造物の山はね現象における破片の到達距離を求めるための基礎データになる．