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The earthquake precursor detected in a granular medium and a proposed model for the propagation of precursive stress-strain signal

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A way to detect the seismic precursor in granular medium is described and a model of propagation for precursive stress-strain signals is proposed. A strain sensor buried in a sandpit is used to measure a seismic precursor signal. The signal has been investigated and confirmed to originate from a specific earthquake. A comparison of simulated and experimental signals indicates that the signal results from the strain in the earth's strata. Based on the behavioral characteristics of granular materials, an analysis of why this method can be so sensitive to the seismic strain signal is undertaken and a model for the propagation of this stress-strain signal is proposed. The Earth's lithosphere is formed of tectonic plates, faults and fault gouges at their boundaries. In the case of the quasi-static mechanics of seismic precursory stress-strain propagation, the crustal lithosphere should be treated as a large-scale granular system. During a seismogenic event, accumulated force generates the stick-slip motion of adjacent tectonic plates and incrementally pushes blocks farther apart through stick-slip shift. The shear force released through this plate displacement causes soil compression deformation. The discrete properties of the sand in the sandpit lead to the sensitive response of the sensor to the deformation signal which enables it to detect the seismic precursor. From the analysis of the mechanism of the stress-strain propagation in the lithosphere, an explanation is found for the lack of signal detection by sensors installed in rocks. The principles and method presented in this paper provide a new technique for investigating seismic precursors to shallow-source earthquakes.

earthquake precursor, earthquake prediction, granular matter, stress-strain transmission, stick-slip movement

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Earthquake is a type of natural disaster that causes tremendous losses of life and property, particularly in China. For a long time, much effort has explored the use of earthquake precursors in earthquake prediction [1,2]. Although our understanding of the links between precursive events and earthquakes has progressed, the extreme complexity of the system has so far not enabled the development of actual earthquake forecasting techniques. The current consensus remains that earthquake prediction is still an unresolved scientific problem. The solution to this problem depends primarily on whether we can obtain reliable information on seismic precursory events and their behavior in connection with physical mechanisms.

This paper describes a way to investigate seismic pre-

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cursors in granular matter, and illustrates the obtained seismic precursory information from designated earthquakes with real examples. A simulation has been performed to compare with *in situ* results. Based on the characteristics of granular behavior, a model for the propagation of a precursory stress-strain seismic signal is proposed. A preliminary analysis of the physical nature of the seismic precursor is presented in a later section.

The key principle behind the approach presented here is that we put our sensor in a granular medium and we treat the crustal lithosphere as a granular system. Granular matter, a ubiquitous class of discrete-state substance, possesses unique kinetic behavior different from that of ordinary solids and fluids [3]. Granular matter has attracted more attention from physicists in recent years [4,5]. Research interests related to earthquakes and granular matter has also grown in the geophysics community [6,7]. This paper makes use of the characteristics of granular behaviors to explain the detected seismic precursor and the propagation mechanism.

1 Method and the sensor

As opposed to established approaches for such work, where a strain sensor is placed on solid rock, we place our strain sensor in a sand pit. A pit, 4 m deep and 2 m in diameter, was excavated in a primitive soil stratum at a selected site. The pit was filled with constructional grade washed sand to a thickness of at least 3 m. The sand was in good contact with the surrounding soil for at least 1.5 m. Three detectors were buried at a depth about 3 m from the top surface of the pit and oriented North-South (N-S), East-West (E-W) and Northeast-Southwest (NE-SW). They were arranged either 0.5 m away from each other in a row or in a triangle with an interval of approximately 1 m. The sand in the pit was pressed tightly after the sensor was buried. A typical setup arrangement is shown in Figure 1(a), and the composition of the sensor is shown in Figure 1(b). The cylindrical cover is made of stainless steel with thickness of 1–5 mm, an outside diameter 0.15 m and a height of 0.4 m, sealed to be waterproof. Inside the cover, a home-made strain sensor [8] was installed to measure the cover deformation. The sensor is calibrated such that 1 mV corresponds to (2.2±0.4) nm in displacement with a linear range of greater than 4 μm and a sensitivity better than 2 nm. Voltage is sent through a bridge as resistance changes because of stress-induced deformation. The sensor output signal is transmitted without any amplification or filtering. Data are then automatically recorded by a data acquisition system at an interval of 1 s. By measuring the deformation of the cylindrical vessel, the strain in the solum can be obtained. The fine tuning unit in Figure 1(b) is used for setting the zero point of the sensor.

The detector is sensitive to the direction of external stress. It responds linearly to the external stress on the cylindrical vessel within a small deformation range. For the external force applied along the axis of the sensor, the sensor generates a signal of pressure deformation. However for a perpendicular external force to the axis, the sensor generates an expanding deformation signal because of the elasticity of the vessel. Once the external force disappears, the elasticity of the vessel enables the sensor to revert to its initial configuration because the vessel is surrounded by sand. The three detectors are oriented in three different directions to help determine the source orientation of seismic precursors.

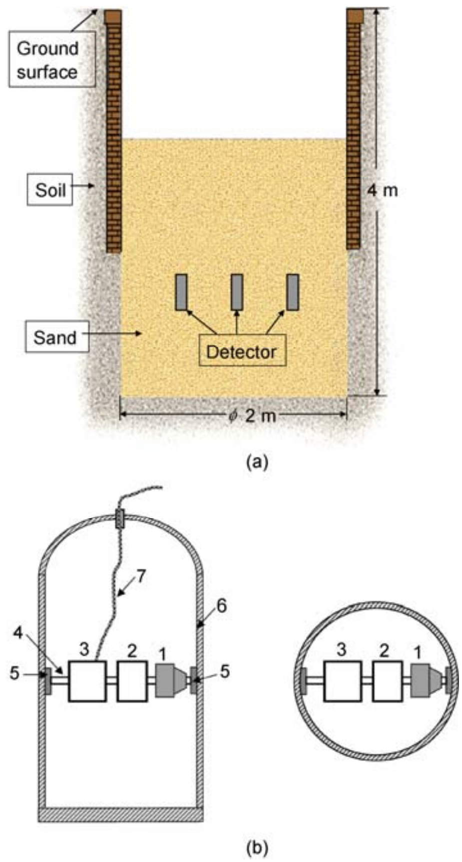

Figure 1 (a) Sketch of a typical detection sandpit; (b) structure of detector: left, side view; right, top view. 1, SW-1 sensor; 2, fine tuning unit; 3, scaler; 4, silica glass pole; 5, insulation holder; 6, steel shell; 7, signal lead.

2 Detection of seismic precursors

Using the granular media detection method described above, we have successfully captured seismic precursory information from the two working stations available so far in Liaoning and Beijing in China. Better examples of precursory signals were recorded for cases like the 1999 *M*5.4 Xiuyan (in Liaoning Province) earthquake, the 2004 *M*8.7 Indonesian earthquake and the 2008 *M*8.0 Wenchuan earthquake [9–12]. The *M*5.4 Xiuyan earthquake occurred on November 29, 1999, very close to our station at Yingkou (only 43 km from the epicenter), and the recorded precursor information was beyond doubt [9]. For the *M*8.7 Indonesian earthquake (December 26, 2004) and the *M*8.0 Wenchuan earthquake (May 12, 2008), significant precursory signals were also detected at epicentral distances of several thousand kilometers because of their large magnitudes [11,12].

Taking the 2004 *M*8.7 Indonesian earthquake as an example, we analyzed the relationship between the main features of the precursory signal and the occurrence of this earthquake. Signals detected at two probe sites, one at Xinmin in Liaoning Province (about 5300 km from the epicenter) and the other in Beijing (about 4800 km from the epicenter) are shown in Figures 2 and 3, respectively. The strain value is defined as the ratio of the deformation to the diameter of the cylinder. The raw data were collected at an interval of 1 s. Figure 2(a) shows the complete data set recorded by the N-S detector from about one year before the earthquake to two months after the earthquake. Note that from January 2004 to mid-November 2004, the recorded compressional deformation increases; the total change is about 1900 nm, corresponding to a strain of 1.3×10^{-5}. This is the cumulative loading regime. In this regime, when the compression deformation is large, fluctuations are suppressed and diurnal variations cannot be observed. About a month before the earthquake, the deformation rapidly declines by about 1700 nm, and reaches its minimum on December 24, and then the earthquake occurs on December 26. As clearly seen in the highlighted region of Figure 2(a), which is enlarged in Figure 2(b), the deformational jiggling corresponds to the earthquake occurrence. The post-earthquake signal is significantly different because after the reduction in stress, a diurnal variation pattern can be distinctly found (Figure 2(c)).

Figure 3 presents the seismic precursor information from the 2004 *M*8.7 Indonesian earthquake recorded in Beijing. Cumulative stress loading is shown for only about 1 month before the earthquake as this detector was just installed two months before the earthquake. The magnitude of compression deformation is about 800 nm, corresponding to a strain of 5.3×10^{-6}. In this regime, the noise and diurnal variation signals are inhibited. A sudden change occurs when the earthquake happened on December 26, and the diurnal variation can again be observed clearly as the stress is relaxed.

Figures 2 and 3 indicate that the main features of the detected signal are consistent. The signals are identified to be from the same Indonesian *M*8.7 earthquake, although they are detected by different stations about 600 km apart in Beijing and Xinmin. Of the three detectors at each station in Xinmin and Beijing, only signals from the most sensitive detectors are shown in Figures 2 and 3. Signals from the detectors deployed at other orientations have similar features, but they are not as pronounced and are therefore not shown here. The fact that the S-N and E-W detectors in Xinmin and Beijing, respectively, were most sensitive demonstrates the sensitivity of the signal recording to orientations. Later in this paper, we will discuss how the local geological environment can affect to the signal, and why the observed signals in Figures 2 and 3 differ.

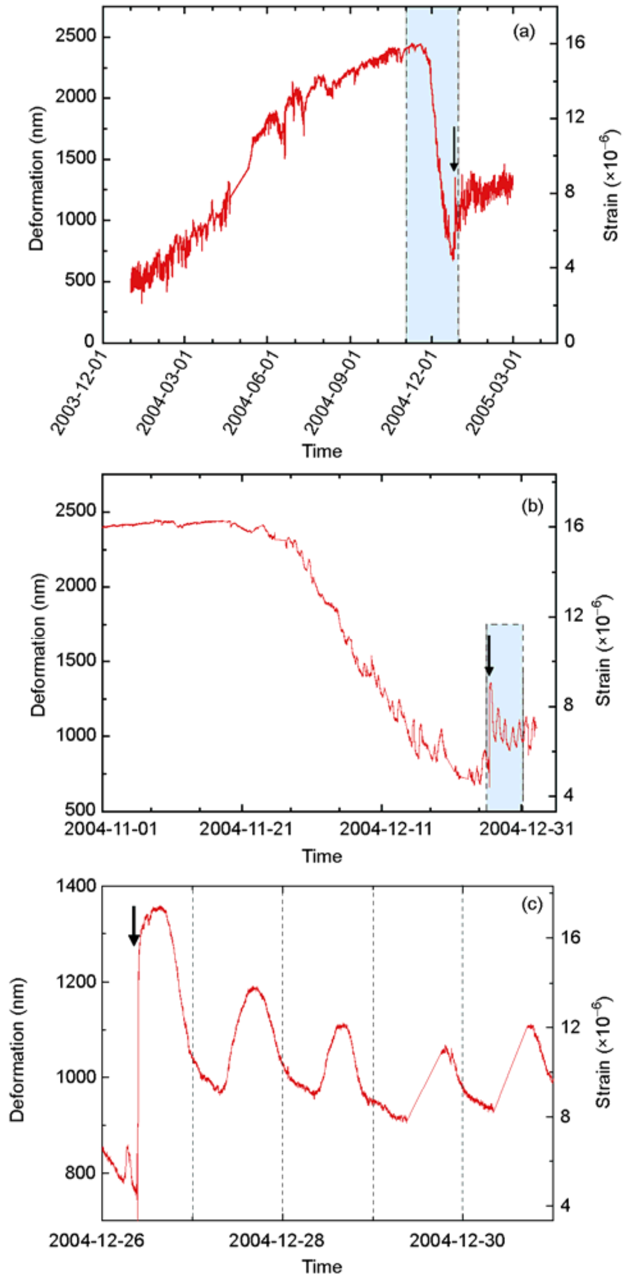

Figure 2 (a) Seismic precursor of the 2004 Indonesian *M*8.7 earthquake recorded with a north-south oriented detector in Liaoning. The interval of the data points is 1 h. Some superimposed events from other earthquakes are seen. (b) An enlargement of the highlighted region in (a). (c) An enlargement of the highlighted region in (b). Dashed lines mark 0:00 time of days. Data point interval is 1 min. Arrow indicates the occurrence time of the *M*8.7 earthquake.

3 Loading and strain detection experiments in granular media

To explore the nature of the detected signals, a simulation was performed. A 2-m-deep sandpit was excavated outdoors

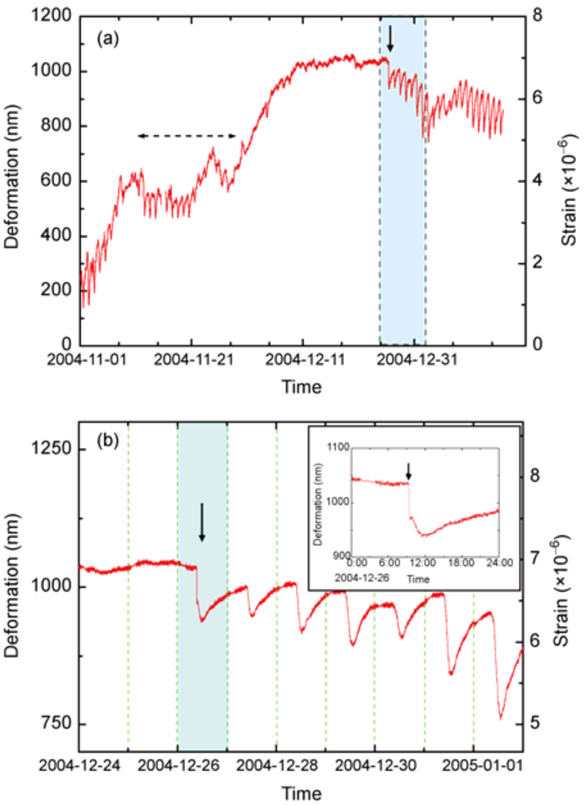

Figure 3 (a) Seismic precursor of the 2004 Indonesian *M*8.7 earthquake recorded by east-west oriented detector in Beijing. There is some superimposed information from other earthquakes as indicated by dashed arrow. (b) An enlargement of the highlighted region in (a). Dashed lines mark 0:00 time of days. Insert shows the signal for the day of the earthquake. Data point interval is 1 min. Arrow indicates the occurrence time of the *M*8.7 earthquake.

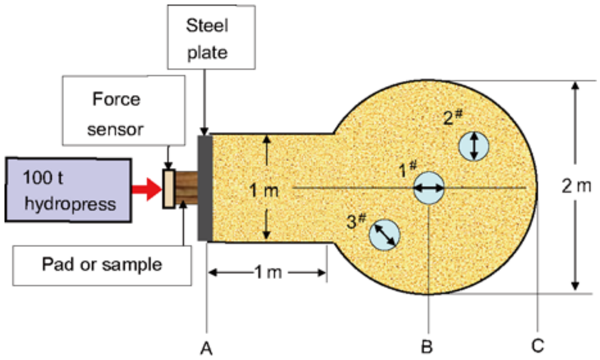

Figure 4 The top view of experimental layout for loading and detecting strain in a sandpit. The square steel plate has sides that are 1 m long and a thickness of 0.03 m. The measuring range of the force sensor is up to 10^6 N, with an accuracy of 10 N. A, B and C represent the forcing point, the center of the first detector and the end point of the sandpit, respectively.

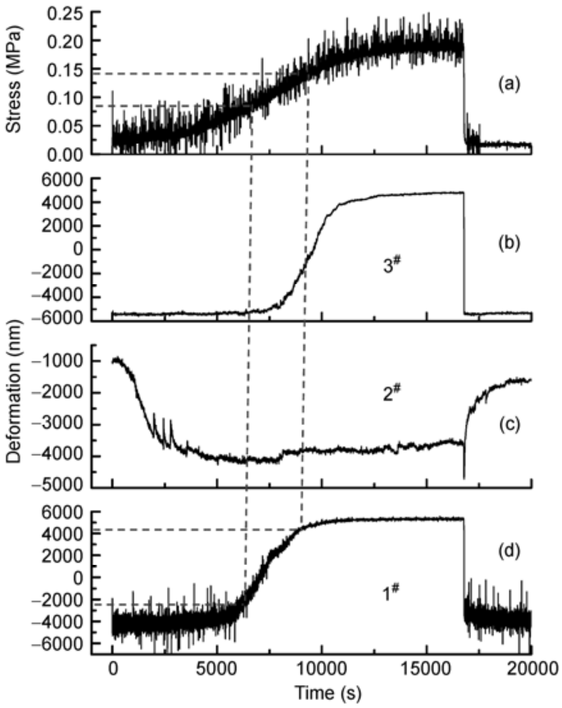

Figure 5 The detected response of loading stress and deformation. The horizontal coordinate is loading time. (a) The process of increasing loading stress. The vertical coordinate is loading stress. (b)–(d) The deformation response of the detectors as labeled. The vertical coordinate is the magnitude of relative deformation.

on the ground, as shown in the design diagram in Figure 4. Construction sand with an average 0.28 mm grain size was used to fill the sandpit to a thickness of 1.8 m. Three detectors with different orientations were placed at the center of the sand layer and arranged in a straight diagonally-oriented (45° to the axis of the sandpit) row with a 0.5 m spacing relative to the direction of applied force. Wall thicknesses of the cylinders for detectors #1, #2 and #3 were 2, 3 and 5 mm, respectively. The sand was compacted and zero points for all detectors were pre-established. A hydraulic press was used to slowly push a steel plate and then exert horizontal pressure to the sand in order to observe the strain response of the detectors. The pressure was measured with a force sensor. Different pads or sample points between the hydraulic press and steel plate (e.g. stones or bricks) can be chosen to observe variation in the strain signal as fracturing or crushing occurs. Figure 5 presents a group of curves showing the applied pressure and the responses of the detectors. From the curve of the applied stress in Figure 5(a), note that the stress has a non-linear increase during the forcing process as determined by the state of the loaded sand. As pressure is applied, the sand gradually changed from a lax to a dense state, and the stress slowly rises. The dense sand, with a larger modulus, can bear a greater stress and thus the exerted stress rapidly increases. When the stress reaches about 0.18 MPa, the stress no longer increases because of the unrestricted upward expansion of sand by the compressive stress. As soon as the hydraulic press unloads, the stress returns to zero immediately. The deformation detected by the three detectors obviously corresponds to the loading stress of Figure 5(a). Detector position, location and elasticity of the cylinder cause some inconsistencies in their measured response. Explicitly, detectors #1 and #3 recorded compressional deformation whereas detector #2 observed expansional deformation, indicating the orientation sensitivity of the stress detectors. A late response for detector #3 compared to detector #1 is due to its thicker shell, i.e. its greater elasticity. This shows that in addition to the force unloading to zero, the elasticity of the cylinder in a detector has a role in returning the sensor back to its initial state. The stress-deformation response of detector #1 is presented to show an example of the stress-strain relationship in the system.

As indicated by theory and experiment [13–15], the elastic modulus of granular matter is related to volume fraction ϕ and stress τ, and expressed as $k \propto \phi^{2/3}\tau^{1/3}$ at a restricted sealed condition. Generally k has a value of tens of MPa for loose sand and hundreds of MPa or more for dense sand [16]. In our experiments, the sand is in a state of compression. There are also effects from the elasticity of the detector shell, placing location and orientation. When the pressure on the sand increases to a certain degree, there is an approximately linear dependence of deformation on the stress in the region of the dotted lines in Figures 5(d) and (a). Then we can characterize this system as an elastomer, i.e. the strain has a linear dependence on stress over this range. If we define an effective elastic modulus $k_{\rm eff}$ for the system consisting of detector #1 and the located sand, then $k_{\rm eff} \approx 1.2$ GPa as calculated by $\tau = k_{\rm eff}\varepsilon$. In the calculation, the stress change $\tau = 0.0053$ MPa is from Figure 5(a) and strain $\varepsilon = (6.67\times10^{-6}\,\text{m})/(150\times10^{-3}\,\text{m}) = 4.45\times10^{-5}$ is from Figure 5(d), where 6.67×10^{-6} m is the deformation and 150×10^{-3} m is the diameter of detector. Therefore, $k_{\rm eff} = 1.2$ GPa reflects the effective elastic modulus in the system of sand and the detector. The assumption for the linear region as a whole makes the computed value of $k_{\rm eff}$ larger. The effective elastic modulus $k_{\rm eff}$ in our experiment and practical detection of seismic precursors is smaller than the modulus of rock (typically on the order of 50 GPa) by about 40 times or more. Thus, the sensitivity of detecting the stress-strain response with our method in granular media must be much higher than that detected in solid rock.

These results show that the detected signal is stress-induced strain. Under the same stress situation, the detected strain in granular media is tens of times more than that detected in solid rock. At the same time, the orientation of detectors can be used to distinguish the direction of stress. These characteristics are beneficial for the detection of seismic precursors.

4 Modeling stress-strain propagation for a seismic precursor

As stated above, an interpreted seismic precursor was identified to originate from an identifiable earthquake and experimental results show that this signal corresponds to strain. The sensitivity of this method to strain detection has been explained. However, to conclusively link this detection method to seismic precursory strain information, there still are three important questions to answer.

(1) Why is the precursory strain signal recorded so far away from the epicenter detected in soil, and how is this signal transmitted?

(2) Why are high sensitivity sensors installed in solid rocks not able to detect the precursory strain information?

(3) Why is the precursory information detected in sandpits placed in different locations not completely consistent?

The essence of the problem is to understand the propagation mechanism of seismic precursory stress-strain information. Based on the study of granular matter and geophysical principles, we propose the model described below for seismic precursory stress-strain propagation to answer these questions.

Shallow earthquakes are commonly thought to originate from rupture or diastrophism in the weak part of the earth's crust under an external force [1,2,17]. Prior to an earthquake, the accumulation of stress can extend over months, years or even decades in the focal area. The strain arising from the stress gradually expands outward and produces the extrusional deformation of strata resulting, in some cases, in observed seismic precursors within a certain range (e.g. a change in groundwater levels). However, the plates, faults and fault gouge of the lithosphere, all of which vary in size, shape, thickness and material, create a complex system that affects the transmission of forces at many scales. Of particular interest is fault gouge containing rock fragments and other granular materials. They are generally in an incompact state, where the elastic modulus is much smaller than that in relatively solid rock. During an actual seismogenic event, the affected region can be very large in scale. Therefore, in a quasi-static mechanical problem addressing seismic precursory stress-strain propagation, the plates and faults of the crustal lithosphere should be regarded as a large-scale two-dimensional granular system, not as relatively homogeneous continuous media.

Figure 6 presents the expansion and outwardly dissemination of precursory stress and strain. As the force of a seismogenic process pushes on rock A in Figure 6(a), the rock overcomes the friction of its boundaries and resistance of the fault gouge resulting in a stick-slip motion [18,19]. Stick-slip motion is quite different from the common continuous displacement of the rock over time, as shown in Figure 6(b). The fault gouge between rocks A and B is compressed like a spring, as shown in Figure 6(c). The density and stress in the fault gouge composed of granular material gradually increases. When the elastic modulus of the fault gouge increases approximately with $\phi^{2/3}\tau^{1/3}$ to a limited extent, the force exerted on rock B through the fault gouge can overcome the resistance of rock B. Then stick-slip motion occurs for rock B as well. This process continues as successive stick-slip motion occurs in rocks as the defor-

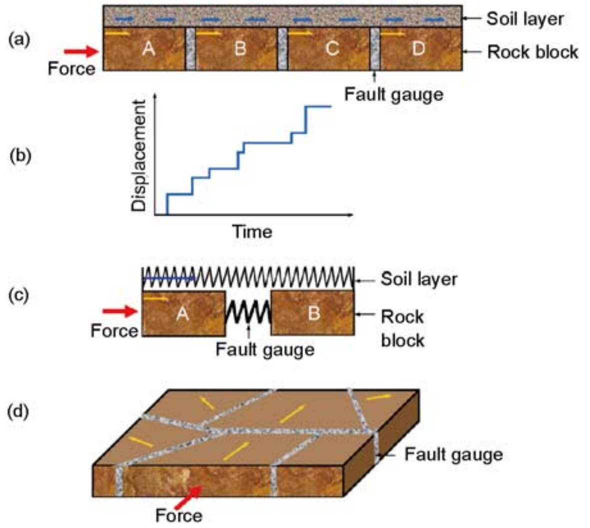

Figure 6 Schematic diagram of seismogenic force inducing stick-slip motion in a rock block, strain of soil layer and propagation of stress-strain.

mation front advances. Because of their large elastic moduli, the rock blocks themselves generate holistic movement as rigid bodies, while the shear displacement and compression mainly are produced in the gaps between blocks and at the boundaries. Incremental stress and strain inside the rocks is small. A few observations have confirmed this mode of motion and the characteristics in the movement of rock blocks. With the method of measuring the creep cross faults, the mutational displacement between faults can be observed prior to an earthquake. Observations of measured creep transition at the fault zone of the Xianshui River in China [20] and several jumping steps observed in dozens of days at the Parkfield SAFOD location in the USA [21] are typical examples.

In discussing the stick-slip motion of a rock block, we should inevitably consider the friction and other obstacles acting on the block, such as friction between the block and the mantle, and the friction and resistance of the fault gouge. In seismogenic processes, the mantle itself also moves because of driving of tectonic forces. The density of the mantle is greater than that of the rock block, but with better fluidity. Therefore, the friction between the rock block and surrounding mantle is much smaller than that between solids, or even individual blocks that are driven by the mantle. Conversely, if the friction between the block and surrounding mantle is similar to that between solids, then the friction would be considerable. For instance, in a case of a rock block with an area of 100 km×100 km and thickness of 10 km, if we take its density as 2.75×10^3 kg/m^3 and friction coefficient as 0.2, then the frictional force to be overcome is up to 5.5×10^{17} N. This means that the stress on one end face of block should be about 0.55 GPa. In practice, however, such a large stress change in rock is never observed. Thus, the motion of rock blocks is perhaps more similar to that of a packed ice floe.

The strain from earth tides can be clearly observed in rocks. Earth tide is the gravitational effect of celestial bodies acting on the Earth, showing either contractive or expansive deformation and resulting in changing the compressive and tensile forces on the rock. The magnitude of detected variable strain of earth tides is typically 2×10^{-8}, a small fluctuation of stress in the rock equivalent to a change of about 1 kPa. However, seismic precursory stress induces rock blocks to generate holistic stick-slip motion and results in an insignificant squeezing stress inside the rocks. This is why the strain of earth tide can be measured while the seismic precursory strain in the rocks cannot. In a typical sample, as measured by Niu et al. [21] the coseismic stress change is less than 2×10^{-8} in rocks at a few kilometers away from the earthquake focus for a *M*3 earthquake. On the other hand, at a long distance away from earthquake focus, the focus area should be regarded as a point source for the force, where the stress decreases with distance r to be as r^{-1} [22,23]. Therefore the variation of precursory stress in the rocks is even more difficult to measure.

The description above led to the inability of obtaining reliable regular information on seismic precursory stress or strain measured in rocks, even with high precision instruments.

The pedosphere, as shown in Figure 6(a), can be defined to lie above the more solid rock crust. When rock blocks take part a displacement event, the interface friction causes a shear interaction to act on the overlying soil. This in turn generates compressive deformation in the direction of rock movement. The soil can be regarded approximately as a quasi-continuous medium, despite its heterogeneity. Because the thickness of the soil layer is much less than its horizontal scale and much thinner than that of a rock block, the compressive deformation in the soil caused by rock displacement would be noticeable. This action can be illustrated with the spring model of Figure 6(c). The transmission of the horizontal forces in the rock blocks must obey the same rule as a chain of granular matter [3], as illustrated in Figure 6(d). Note the change in the direction of the force and the block motion. Tangential displacement and dislocation may also appear in rock blocks, so that not only compressive strain but also tangential strain may occur in the upper soil layer.

The scale of plates or faults can be tens, hundreds or even thousands of kilometers. Under the action of external forces they generate consecutive holistic stick-slip motions with fast or slow speeds. The motion through a whole block (or even several blocks) is almost simultaneous. Some observed synchronized movements in large-scale blocks [24] may, in fact, be caused by such motion. Note that (1) the velocity of stick-slip motion of whole large-scale block, (2) the time lag of the relative displacement between the boundaries of a block, and (3) the velocity of acoustic propagation are different concepts. The velocity of acoustic propagation in rock strata (several km/s) is related to the nature of media. For the displacement at the boundary endpoints in the same block, there is no time difference for a rigid body, whereas there may be a small time difference for the actual blocks because of internal non-uniform plastic deformation. The velocity of holistic stick-slip motion of a block can be high or low, and the magnitude and direction will depend on the force, resistance and traits of the rock block. The motion of a block as a whole can be mutational or quasi-continuous [20, 21]. The deformation of soil driven by the rocks is generally continuous or characterized by damped hopping because of its low elastic modulus and viscoelasticity. As shown in Figure 6(d), the direction of motion for different blocks may be inconsistent with the direction from the earthquake focus to observation point, depending on the geological conditions encountered along the travel path of the signal. The sensitivity to the orientation of the detectors set in a sand bunker not only depends on the moving direction of the rock block below, but also the surrounding geological environment.

Each stick-slip motion of a whole block occurs at a scale of magnitude from μm to mm [20, 21]. The accumulated movement of the rock may be bigger for a larger earthquake. Although GPS measurements can observe the accumulated displacement of the earth's surface, such techniques are unlikely to detect an individual stick-slip movement with current resolution capabilities. However, the motion of the rock must drive the soil layer to be deformed. This deformation can be detected with our detector, of which the sensitivity of is about 2 nm, i.e. 1.3×10^{-8} for strain measurement. In some cases, our actual measurement of accumulated deformation over a long term can reach up to the order of μm or even saturate the measurement capabilities of the detector. As previously mentioned, the detected strain in the soil can be about 10^{-5} at locations even thousands of kilometers away from epicenter of a large earthquake. However, the precursor information detected at various probing stations will differ because of varying geological conditions, differing magnitudes and directions for the displacement of rock blocks, and the deformation of soil related to its location and physical nature.

Therefore, precursory information detected with our approach is actually a measurement of local strain in soil, which is induced by seismic precursory stress propagation. The detectors are placed in a sandpit instead of buried directly in the soil to remove the effect of plastic deformation in squeezed sticky soil. The discrete characteristics of granular matter enable the elastic deformation of the detector cylinder to be mostly restored after the extrusion disappears, so that the detector—over a certain range—can maintain an approximately linear response for stress and strain.

Our model suggests that precursory stress is spread to overlying soil layers through the shear action of underground rock blocks, rather than spreading along the earth surface. Therefore intervening terrain and geomorphology on the earth's surface (e.g. mountains, rivers, lakes and seas) will not impact significantly on the detection of precursory information.

5 Discussion

The use of the proposed model can readily explain the examples of seismic precursors shown in Figures 2 and 3. Prior to the 2004 Indonesian *M*8.7 earthquake, the stress that gradually accumulated at the earthquake focus led to the generation of stick-slip movement in the crustal blocks. The stick-slip motion was successively transferred to other blocks along with an increase in stress accumulation. When the accumulated stress was large enough, the motion of the rock blocks in the vicinity of the detection point also occurred and generated compressional deformation in the soil through the shear action of the blocks. For large earthquakes, strain accumulated through seismogenic processes can impact an area up to thousands of kilometers in diameter, so it is reasonable that the detection stations in Liaoning and Beijing should receive clear deformation signals showing a continuous increase with increasing accumulated stress from as far away as Indonesia. Recorded deformation and strain at the two stations were 1900 nm and 1.3×10^{-5}, and 800 nm and 5.3×10^{-6}, respectively, showing the extent of strain accumulation in the soil. Note in Figure 2 and in other detected precursors examples [9–12] that there was mostly a rapid decline in strain prior to the earthquake. One possible reason for this phenomenon is the Reynolds expansion effect [18]. The principle of Reynolds expansion in granular matter is that the applied force will lead to volume expansion for granules originally in a dense state, and then further pressure will cause volume shrinkage as expansion reaches a certain limit. The same effect should occur in strata consisting of granular systems, where volumetric expansion or contraction depends on the local geological environment. For example, groundwater levels are somewhere observed to rise and at other places to fall in observed seismic precursor events. The observed strain drop prior to the earthquake in this case may be caused by a similar process whereby the stress is accumulated to a level where a further squeeze will lead to the contraction of the volume of the local area and result in a reduction of strain in the soil. This is also related to local geological conditions and orientations, so the results may differ from region to region. Further investigation is needed if the cause of this rapid decline in precursory strain prior to the earthquake is also connected with the yield of rock units at the earthquake focus. Once the earthquake occurs, the stress must be quickly relaxed and returned to a low stress state. Correspondingly, as shown in Figures 2 and 3, a clear and regular diurnal variation signal appears after the earthquake. Our detected diurnal variation differs from both the solid earth tide and the anticipated temperature effect in the detector. A possible cause of this phenomenon is the expansion and contraction in the local strata due to the temperature differences between day and night. This remains to be studied further.

Figures 2 and 3 reflect the complete picture of strain variation for the 2004 Indonesian *M*8.7 earthquake during its gestation, rupture and after-shock processes. Similar behaviors have been observed by this method for other earthquakes [9–12]. The processes and behaviors are coincident with a physical model of crustal deformation recognized by seismologists for shallow earthquake preparation [1,2,25,26]. However, the detected signals for different earthquakes—or for a same earthquake recorded at different locations—are subject to the earthquake response and geological environment along the path of the stress-strain transmission, and also to the inbuilt status of the detectors. The dissimilarities between Figures 2 and 3 come from those factors. In addition, there may be other earthquakes building and rupturing elsewhere in the vicinity during the period, which could overprint the observed signals. These earthquakes potentially could be related by their magnitude and location and thereby be distinguished as part of the earthquake detection process.

The model shown in Figure 6 also provides clues as to how to choose an appropriate location for the detection equipment and how to determine the orientation of the precursory signal. Optimal deformation signal reception should occur by burying the detector at some distance from the edge of individual rock blocks, where the relative displacement between blocks may be larger and the deformation of soil will be more evident. It is also better to deploy the detectors for a particular site in original low-viscosity high-density soil. An in-depth knowledge of geological conditions such as faults and the local environment of the earth surface near the detection point will help in the analysis of precursory signals and also to improve the directional sensitivity from an array of directional detectors.

The issue of stress-strain propagation discussed above relates to the status of two features for granular matter. First, we collectively treat the rock blocks as a granular system in which the granular size is large but in which the system contains a relatively small number of "grains". In this case, the force chain structure and the stick-slip movement play a major role. This is fundamentally different from handling crustal rocks as continuous media and causes completely different characteristics in the modeled motions of the rock mass. The force chain structure of rock blocks will determine the sensitivity of a particular sampling station. The rock blocks of a stronger force chain can generate larger stick-slip motion and the corresponding detector station positioned in soil can record a clearer precursory signal. Second, the detection is performed in a sandpit where a system with a large number of granules can be treated as a quasi-continuous medium [4,14]. However, because the soil and sand belong to a dissipative system with a low effective elastic modulus, only quasi-static stress-strain with low frequencies can spread easily. This is quite different from the propagation of seismic waves in rocks. It is for this reason that the detection method is not very sensitive to co-seismic change in our measurement, as shown in Figures 2 and 3. The recorded mutative time should usually be later than the arrival time of the seismic wave. The mutative time recorded at Xinmin was 9:28 on December 26 as shown in Figure 2 and 9:17 at Beijing as shown in Figure 3, whereas the earthquake happened at 8:58:55 on December 26 (all are in Beijing time). This fact indicates that the mutation in our records is due mainly to localized stress relaxation near the detection stations after the earthquake.

Because the structure of the earth's crust is very complex, the transmission and exploration of seismic precursory stress-strain systems are closely related to the seismic type, the distribution of blocks and the geological environment. An in-depth understanding of the local geological setting in the area around the seismic focus and recording point is most important for judging the correspondence of a detected precursor and an earthquake. On the other hand, analyzing detected precursory strain from different recording stations with this method must provide valuable information for understanding the geological setting.

6 Conclusions

The deployment of stress-strain detectors in sandpits at the earth's surface has successfully enabled the recording of precursory signals, which correspond to identifiable earthquakes; these signals have regularity as well as directional sensitivity. Experiments and analyses indicate that the detected signal corresponds to strain variations arising from the build-up to an earthquake and its subsequent rupture. By treating the crustal plates and faults as a granular system, based on the characteristics and motion laws of granular matter, a model for the extension and propagation of a seismic precursory stress-strain field has been proposed. Forces exerted during the build-up to a seismic event produce the stick-slip motion of a rock block as a whole, which in turn gradually pushes other blocks and gets them moving as well. Any shear action of the block motion can generate compressive deformation in the soil layer, of which the variation can be readily detected by the instrumentation placed in a sandpit detector unit. Rock units will return to their relaxed state, accompanied by a stress reduction, after the earthquake. The detection of a precursory seismic signal conforms to commonly admitted physical models for the seismogenic crust where earthquake precursory activity and generation occur. By analyzing the stress-strain propagation mode of a seismic precursor in strata and contrasting this to the physical nature of granular matter and rocks, it is readily seen why seismic stress-strain precursors can be detected by our method but largely overlooked in rocks. Although the detection of shallow earthquake precursors using the proposed method has been achieved "after-the-fact", and preliminary discussion of the physical mechanisms causing the phenomenon has been made, many issues need further intensive study because of the complexity of the earthquake process. By further improving the detection method, setting up additional recording stations to get more precursory information on the actual earthquake, and strengthening related research, this approach could become an effective way for detecting seismic precursory signals.

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