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THE MECHANICS OF STICK-SLIP[1]

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SUMMARY

Physical mechanisms that have been proposed to explain the occurrence of stick-slip motion during frictional sliding have been examined in the light of results obtained from experiments with rocks and brittle minerals. An instability caused by sudden brittle fracture of locked regions on surfaces in contact is the most likely explanation for stick-slip during dry frictional sliding of brittle rocks at room temperature. Areas requiring further study and the uncertainties in applying the results of laboratory experiments to earthquake studies are emphasized.

INTRODUCTION

It has been observed that motion on fault surfaces, such as the San Andreas fault, can take place suddenly to produce an earthquake. During sudden slip shear stress is relieved, and the fault surfaces may then remain locked together until at some later time slip takes place suddenly again. Such sudden intermittent motion on pre-existing faults in the earth is similar to the sudden intermittent motion that has been observed during frictional sliding between rock surfaces in laboratory experiments. In our laboratory experiments, we describe this jerky type of motion as stick-slip.

A number of theories, most of which have appeared in the engineering literature, have been proposed to explain the mechanics of stick-slip. The purpose of the present paper is to review these theories and to point out the areas of uncertainty in applying the results of our laboratory experiments to earthquake studies.

GENERAL

Fig. 1 is a schematic representation of a typical friction experiment. A rider of mass m is free to slide on a rigid flat. The tangential force required to move the rider is applied through a spring AB. If the point B is moved to the right at a low velocity v, the force in the spring will increase

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with time until the force is sufficient to overcome the frictional force. If the rider then moves forward suddenly at a velocity greater than v, the force in the spring will decrease and the rider will eventually stop. The rider will remain stationary until the force in the spring once more builds up to a value sufficient to overcome the frictional force.

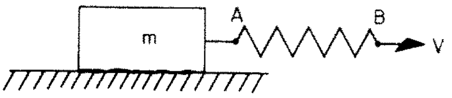

Fig. 1. Schematic diagram of a typical friction experiment. m = mass; AB = spring applying tangential force; v = velocity.

The classical explanation for this jerky type of motion is that static friction is greater than kinetic friction. It is assumed that once motion occurs between the rider and the flat friction falls suddenly to a lower value. The force in the spring is now greater than the force required to maintain sliding, so that the system is unstable and the rider will accelerate.

The differential equation for the motion of the rider on the flat can be derived by adding all the forces acting on the rider during its motion and equating this sum to zero:

$$m \frac{\mathrm{d}^2x}{\mathrm{d}t^2} + A \frac{\mathrm{d}x}{\mathrm{d}t} + \mathrm{f}\left(\frac{\mathrm{d}x}{\mathrm{d}t}, x, t_0\right) + K(x-vt) = 0$$

where $m(\mathrm{d}^2x/\mathrm{d}t^2)$ is the inertial force of the accelerating rider of mass m, $A(\mathrm{d}x/\mathrm{d}t)$ is the damping, generally considered to be a linear function of the velocity, $\mathrm{f}(\mathrm{d}x/\mathrm{d}t, x, t_0)$ is frictional force, which may be a function of the velocity of the rider, time of stationary contact between the surfaces, and relative displacement between the rider and the flat and $K(x-vt)$ is force in the spring, where K is the spring constant.

Numerous solutions to this equation have appeared in the published literature (Thomas, 1930; Block, 1940; Sampson et al., 1943; Dudley and Swift, 1949; Singh and Push, 1957; Push et al., 1957; Derjaguin et al., 1957; Bowden and Tabor, 1958; Singh, 1960; Hunt et al., 1965; Brockley et al., 1967; Banerjee, 1968; Jaeger and Cook, 1969). In this paper we will not discuss these mathematical developments, rather, we will concentrate on a discussion of the physical mechanisms that have been proposed to explain why stick-slip can occur during dry frictional sliding of one surface over another. Basically there are four theories: (a) instability due to thermal softening; (b) instability due to creep; (c) plastic instability; and (d) brittle instability. Each of these theories will be discussed in the light of recent experimental results from studies with rocks and brittle minerals.

Instability due to thermal softening

Bowden and Leben (1939) showed that during sliding there is an increase in temperature at sliding surfaces. This led to the idea that kinetic friction could be less than static friction because the temperature rise during rapid sliding may lower the strength of the material. One situation where this is observed is where the velocity v in our model in Fig. 1 is very high. In this case the relative velocity between the rider and the flat never reaches zero. The temperature at the sliding surfaces can increase to the melting point and the rider then vibrates in a simple harmonic plus translatory motion (Rabinowicz, 1959).

The theoretical analysis of Griggs and Baker (1969) has shown that an instability due to thermal softening can occur during shear, even though the shear stress may be applied slowly enough for the temperature to fall well below the melting point between the successive slips. A significant result from the theoretical analysis is that a period of stable non-elastic deformation always precedes sudden shearing. The reason for this is that in this model the strength of the material is determined by the instantaneous temperature, but the temperature cannot increase until shearing commences.

It has been proposed that this mechanism of thermal softening may be mechanism for deep-focus earthquakes (Orowan, 1960; Griggs and Baker, 1969), but there are at least two reasons why this mechanism cannot explain the instability that may occur during sliding between rock surfaces at room temperature. First, the mechanism clearly requires a period of stable sliding to precede sudden slip, but in our laboratory experiments it is often found that slip takes place suddenly without any detectable non-elastic deformation before slip (Brace and Byerlee, 1966; Bromwell, 1966; Dickey, 1966; Byerlee, 1967a; Byerlee and Brace, 1968; Byerlee and Brace, 1969). Second, examination of the surfaces of brittle materials after sudden slip has shown that the wear particles produced during sliding in experiments at room temperature are produced by brittle fracture of the minerals (Byerlee, 1967a; Byerlee, 1967b). There is no evidence to indicate that the temperature during sliding has been high enough for melting to occur.

Even though stick-slip may in some cases be preceded by stable sliding (Byerlee, 1967a; Byerlee and Brace, 1968; Scholz, 1968) so that the sliding characteristics may bear a superficial resemblance to what would be expected if thermal softening were the controlling mechanism, the absence of any evidence for melting shows that the instability in these room-temperature experiments must be due to another mechanism.

Instability due to creep

In the creep theory for stick-slip, which was originally proposed by Ishlinski and Kragelsk (1944), it is assumed that static friction is a function of the time of contact between the surfaces. The model for this theory is that when the rider is at rest, the junction at the points of contact between the surfaces deform by a creep mechanism so that the size of the junctions increase with time. During sliding, the time of contact is so small that junction growth does not occur. If the frictional force is the force required to shear the junctions, then the force required to start sliding after the rider has been at rest may be greater than the force required to maintain sliding. Hence static friction could be greater than kinetic friction.

An objection to the creep theory is that it assumes that the force required to shear the junctions is determined by their size alone. And this assumption is incorrect, because the force required to shear the junctions is determined not only by their size, but by the shear strength of the material as well. If we assume that the dynamic compressive strength of the material is high, so that junction growth is inhibited, we must also assume that the dynamic shear strength of the material is high as well. Thus, it should make no difference whether the junctions are large and weak or small and strong, the friction should be the same in both cases.

A critical test of this theory for rocks was made by Byerlee and Brace (1968). In their experiments, cylindrical specimens of granite containing saw cuts oriented at an angle of 30° to the axis of the cylinders were subjected to confining pressure. Frictional sliding on the saw cuts was then studied as a function of the rate at which the load was applied to the ends of the specimens. In each experiment, sliding was by violent stick-slip. At the fastest loading rate, the time of stationary contact between sudden slips was several minutes; at the slowest loading rate, several hours. It was found that there was no correlation between the force required to initiate sudden slip and the time of stationary contact between the surfaces. As this observation is clearly contrary to what the creep theory would predict, the instability in these experiments must be due to another mechanism.

Plastic instability

The work of Rabinowicz (1959) has led to a great advance in our understanding of the mechanics of stick-slip. He proposed that the frictional force varies, rather than be constant, with relative displacement between rider and flat.

One case to which this applies is the sliding of clean, like metals. When we start to move one surface over the other, the junctions at the points of contact grow in size. During this period of junction growth, friction increases. A stage is reached, however, when the junctions stop growing and begin to thin out and eventually break. During this period, friction falls. The process is repeated and the frictional force required to cause sliding fluctuates with relative displacement between the rider and the flat. In the extreme case, the surfaces become severely damaged due to galling.

Fig. 2 is a typical frictional force displacement plot for such a mechanism. If, we measure displacement of the rider in Fig. 1, positive to the right, then if the rider suddenly slides at a velocity much greater than v, we can safely neglect the extension of the spring due to the movement of point B. The force F in the spring will then decrease according to the relationship:

$$F = -K_1 x$$

where x is the displacement of the rider and K_1 is the stiffness of the spring. We can plot this function as a straight line with slope $-K_1$ on our frictional force displacement plot in Fig. 2. If we move point B in our

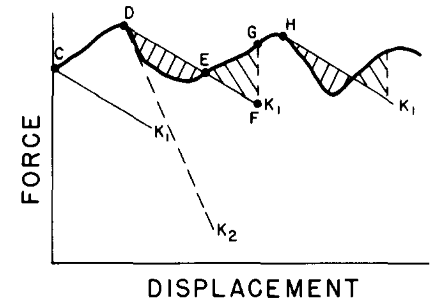

Fig. 2. Hypothetical friction force displacement plot of point A in Fig. 1.

model on Fig. 1 slowly to the right, the force in the spring will gradually build up until it is equal to the frictional force at point C in Fig. 2. The rider will then commence to move at a velocity slightly lower than v because the friction is increasing with displacement. The stable sliding will continue until point D in Fig. 2 is reached. At a displacement slightly greater than D, the force required to cause sliding will be less than the force in the spring and this unbalance of forces will accelerate the rider. If the mass of the rider is small and damping of the system can be neglected, then the velocity of sliding will be high, so that we can safely neglect the extension of the spring due to the movement of point B in Fig. 1. The force in the spring will then decrease along the straight line DE, which has the slope $-K_1$, the spring constant. The shaded area above the friction line has dimensions of force by displacement and represents the kinetic energy gained by the rider during the period of acceleration. Beyond point E, the force in the spring is less than the friction force and the rider will decelerate and eventually come to rest at point F when the shaded area above the friction line is equal to the shaded area below. The rider will now remain at rest until the force in the spring increases from F to G, at which point stable sliding will recommence. Stable sliding will continue until point H is reached, when the fall-off in frictional force with displacement occurs at a greater rate than the fall-off in spring force with displacement.

If, as is usually done, we plot force in the spring as a function not of displacement of point A, but of point B in Fig. 1, then we will get the curve as shown in Fig. 3. There will be an initial elastic increase in force followed by a period of stable sliding, then a sudden drop in force shown by the dashed line during sudden slip. The cycle is then repeated.

Rabinowicz (1959) found that the magnitude of the force drop during sudden slip between metal surfaces could be reduced by increasing the stiffness of the loading system. In fact, in some cases stick-slip could be completely eliminated. The explanation for this is that with a stiff spring, say with a slope of $-K_2$ in Fig. 2, the force displacement curve for friction never falls at a rate greater than the loading system is capable of following. In this case, the sliding velocity of the rider fluctuates about the velocity at which the point B, in our model of Fig. 1, is moved to the right. The system never becomes unstable, however.

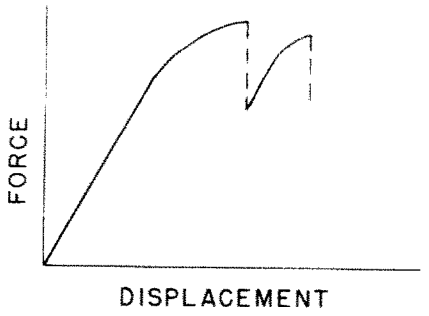

Fig. 3. Force displacement plot of point *B* in Fig. 1.

In the friction model just considered, the instability arises because friction fluctuates during plastic deformation of the junction on the surfaces in contact. While plastic deformation may occur during the sliding of some rocks such as limestone, dolomite, and rocks rich in serpentine, chlorite, and talc, the theory of plastic instability would not be adequate to explain stick-slip motion between surfaces of extremely brittle rocks, like granite, at room temperature.

Brittle instability

Byerlee (1967a, b) proposed that when two surfaces of a brittle material are placed together, the asperities on the surfaces in contact become locked together. If the normal load is high enough to prevent the surfaces from lifting up over the irregularities, then sliding will occur when the locked regions fail brittlely. In this model, the frictional force is the force required to break the interlocking irregularities, and if sliding occurs in this way, the friction force will increase when the surfaces become locked and decrease when the locked regions are ruptured. If this process is repeated, the friction will fluctuate with relative displacement between the two surfaces, and, as in the model of plastic instability, stick-slip will occur whenever the decrease in friction with displacement occurs at a rate greater than the loading system is capable of following.

This model of brittle instability for stick-slip is supported by the observations of a number of workers in the field of friction. For instance, when a diamond stylus is moved over a surface of lithium fluoride, the sliding is accompanied by plastic deformation but cracking also occurs, and it is significant that the cracks appear to coincide exactly with the beginning of the slips in the stick-slip process (Steijn, 1964). Similarly, cracking occurs when a stylus is moved over a surface of rutile, and the cracking here is also accompanied by violent jumps in friction (Steijn, 1969). Brittle fracture occurs during the sliding of a rough, flat slider or a sharp stylus on diamond. In this case the friction is anisotropic and the greatest damage to the surface is produced in the direction of high friction (Bowden et al., 1964). It seems significant that in this direction the sliding is by violent stick-slip (Seal, 1957). With a blunt or smoothly rounded stylus sliding on diamond in air or a moderate vacuum, the sliding is smooth and the surface shows no perceptible wear. Under a high vacuum, however, the wear to the surface is considerable and is due to brittle fracture of the diamond (Bowden and Hanwell, 1964). Under these conditions stick-slip is pronounced (Bowden and Young, 1951). During the sliding of rough surfaces of rock or rock-forming minerals on a rough surface of sapphire, the movement is by violent stick-slip and a large amount of wear particles is produced by brittle fracture of the softer material (Byerlee, 1967b). If, on the other hand, the sapphire is finely ground or polished, the magnitude of the force drop during slip is very small or absent, and it seems significant that in this case the wear to the surface is only superficial (Byerlee, 1967b). Two rock surfaces may also slide by slick-slip, and here too brittle fracture of the minerals occurs during sliding (Jaeger, 1959; Byerlee, 1967a, b).

Thus, there is ample evidence to indicate that brittle fracture is a very important process during the sliding of brittle materials, and there is a high correlation between the amount of fracturing involved and the severity of the stick-slip process. A model for stick-slip based on brittle instability would therefore be applicable to the sliding of brittle materials like rocks and rock-forming minerals at room temperature.

With metals it has been possible to determine the force displacement function during sliding because the sliding can be stabilized by using a very stiff machine so that a force–displacement plot such as that shown in Fig. 2 can be determined experimentally (Rabinowicz, 1959). With rocks, however, the decrease in friction with displacement is often so abrupt that it has not been possible to stabilize the sliding, even when we make the stiffness of the system as high as $2 \cdot 10^5$ kg/cm (Byerlee and Brace, 1968).

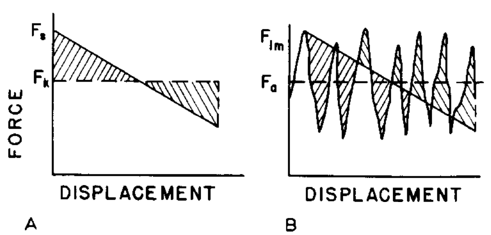

Fig. 4. A. Force displacement plot for constant kinetic friction. F_s, static friction; F_k, kinetic friction. B. Force displacement plot for fluctuating friction. F_{lm} = local maximum; F_a = average frictional force during slip.

It has been found that for sliding between finely ground surfaces of granite at high confining pressure the magnitude of the force drop during sudden slip is independent of stiffness (Byerlee and Brace, 1968). This could occur if, during sudden sliding, the kinetic friction is a constant independent of the displacement between the surfaces. Fig. 4A shows a plot of force as a function of displacement for this mechanism. F_s is the static friction, F_k the kinetic friction. During sudden slip, the force in the spring in Fig. 1 falls along the straight line with a slope of $-K$, the spring constant. The rider will come to rest when all the kinetic energy gained by the rider during the period of acceleration is used up during the period of deceleration. If the damping of the system is negligible, then the force drop during slip will be $2(F_s - F_k)$ independent of the stiffness of the loading system.

This mechanism would explain our experimental results, but it does not seem reasonable because we would expect that during sliding some asperities would become locked and then broken and after a short distance of sliding other asperities would jam together and these would then break. If this occurred, the friction would not be a constant but would fluctuate rapidly with displacement between the two surfaces. In this model, shown schematically in Fig. 4B, stable sliding will occur until the local maximum in friction F_{lm} is reached. At this point, the rider will suddenly accelerate. If, during sudden sliding many maxima in friction are exceeded, the rider will be subjected to many periods of acceleration and deceleration. The average frictional force during slip will be F_a. The force drop during slip will be $2(F_{lm} - F_a)$. The local maximum may vary between wide limits so that the force drop may not be the same for successive slips, but in a sufficient number of trials, the average value of the force drop will be independent of the stiffness of the loading system.

Thus, as was pointed out by Simkins (1967), it makes no difference whether friction fluctuates rapidly with displacement so that the average value is F_a or, as in the classical explanation for stick-slip, friction falls suddenly to a constant kinetic friction F_k. The results will be the same in both cases.

In the classical explanation for stick-slip, it is difficult to explain physically why the kinetic friction should drop so abruptly as the surfaces commence to move and then remain constant. This difficulty, however, does not arise if the instability occurs by sudden brittle fracture of the locked regions on the surfaces in contact.

In our model, the irregularities on the surfaces become locked, fail brittlely and then lock again, and there is evidence to indicate that this does in fact occur during sliding between rock surfaces. With repeated sliding, however, the broken material accumulates and the sliding conditions change. In the extreme case, such as sliding on a fault surface produced in initially intact rock, a large thickness of fault gouge is developed and at low normal stresses the sliding is stable (Jaeger, 1959; Maurer, 1965; Byerlee and Brace, 1968). Small shocks which can only be detected ultrasonically occur during stable sliding (Scholz, 1968), but apparently the individual grains in the loosely packed material can break and, or move with respect to one another during shear without the process becoming catastrophic.

At high confining pressure, however, shearing of a rock powder is macroscopically unstable, even if the specimen is composed entirely of crushed rock (Byerlee and Brace, 1969). It would seem reasonable to suggest that at high pressure the grains become so densely packed together that failure of one grain may lead to a large enough increase in stress on the adjacent grains that the process could become unstable.

Density of packing, however, is not the only factor involved, because in a densely packed material in which the grains are surrounded by even a very thin layer of a weak alteration mineral such as serpentine, the pressure at which unstable deformation occurs is markedly increased (Byerlee and Brace, 1968). Perhaps this is because the weak material acts as a solid lubricant, making it easier for the grains to lift over one another during shear; but unfortunately we do not have enough evidence to either prove or disprove this possibility.

Hoskins et al. (1968) suggested that stick-slip is important only if the surfaces are finely ground or polished. This is not correct, because rough fault surfaces may slide by stick-slip if the confining pressure is high enough, and even at low normal stresses rough surfaces slide by stick-slip if the sliding is stopped before a large thickness of fault gouge has developed (Bromwell, 1966; Dickey, 1966; Byerlee, 1967a). Furthermore polished surfaces of brittle materials may slide stably if the normal stresses are very low (Horn and Deere, 1962; Byerlee, 1967b).

The reason for Hoskins et al. finding the sliding of rough surfaces smooth was most probably that with repeated sliding, a large thickness of detrital material developed and the normal stress in their experiments was low enough for this material to deform stably. With their polished surfaces, however, there was little evidence for detrital material, and apparently the normal load was high enough for the irregularities on the surfaces to become jammed together so that the sliding was by stick-slip.

CONCLUSIONS

When we recognize that stick-slip is really no more than an instability problem, it is clear that stick-slip will occur whenever the frictional force decreases with displacement at a rate greater than the loading system is capable of following. With clean, like metals sliding on one another, the decrease in friction with displacement is caused by plastic shear failure of the junctions on the surfaces. With brittle rocks, the instability during sliding is probably caused by sudden brittle failure of the interlocked irregularities on the surfaces. Other mechanisms such as thermal softening and creep do not appear to be important factors in room-temperature sliding of brittle rocks.

Although the mechanism of brittle instability can explain stick-slip, the theory in its present form is only a qualitative one and is therefore not completely satisfactory. Ideally, we would like to be able to predict with some degree of certainty whether stick-slip or stable sliding will occur in any given situation.

We know that with polished surfaces of brittle materials, the sliding will be stable if the normal stress is low, but unstable if the normal stress is high. Unfortunately, we cannot at present predict the stress at which the transition takes place.

Another area in which there is a great deal of uncertainty is the sliding of fault surfaces when a large amount of fault gouge is present. We know that in this situation also sliding is stable at low normal stresses, but unstable at high normal stresses. On fault surfaces produced in unaltered silicate rocks in room temperature laboratory experiments, the transition from stable to unstable sliding takes place at a confining pressure of about 2 kbar (Byerlee and Brace, 1968). We cannot say with certainty that this will also be the transition pressure between unstable and stable sliding on natural faults in the earth, because we do not know exactly what determines the transition pressure. Is it a function of the thickness and grain size of the fault gouge or the out-of-flatness and area of the moving fault surface, or is it independent of these factors?

From our laboratory experiments we know that a small amount of weak alteration minerals may have a large effect on the transition pressure, and this factor must be taken into consideration in applying our results to the earth, because in the earth the fault gouge may be extensively altered by migrating fluids.

In our laboratory experiments with ground surfaces of granite, the stability of sliding was not affected by strain rate (Byerlee and Brace, 1968) or pore fluids under pressure (Brace and Byerlee, 1966), but the effect of these factors on the stability of sliding of fault surfaces when a large amount of fault gouge is present has not been systematically studied.

In the earth the rocks may be at high temperature, particularly in the mantle, but earthquakes still occur to a depth of about 700 km. At depths of this order the instability may be caused by thermal softening, as suggested by Orowan (1960), or it could be due to sudden phase changes, as suggested by Benioff (1964). Unfortunately, the effect of high temperature and pressure on the stability of deformation of rock has not been studied in sufficient detail for us to prove or disprove either of these hypotheses. It has been suggested (Isacks et al., 1968) that cold crustal material is being thrust down into the upper mantle in the regions where deep-focus earthquakes occur. If this is true, then we cannot rule out the possibility that in these regions the earthquakes may simply be caused by a brittle instability, especially if pore fluids under high pressure are generated at these depths by dehydration reactions of hydrous minerals (Raleigh and Paterson, 1965).

One problem that has puzzled seismologists is that the stress drop during slip in our small laboratory specimens can be as high as several kilobars, but the stress drop during even very large earthquakes is rarely greater than 100 bar. Is this a size effect or is it due to other factors?

One way in which our laboratory experiments differ from the natural situation is that in our small samples the fault intersects the boundary of the specimen whereas in the earth only a finite length of the fault moves during an earthquake. When this movement occurs, large stresses are developed at the ends of the slipped section (Chinnery, 1967). Recent work by Dieterich (1969) has shown that under these conditions, the average shear-stress drop during sudden slip is about an order of magnitude lower than what it would be if the fault were free to move unhindered by the surrounding material. Thus the result of our laboratory experiments may be applicable to the natural situation if allowances are made for the fact that the geometries are different.

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