ICE SLIDES AND GLACIER SURGES

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Summary

There are natural hazards in mountain regions caused by abrupt glacier surges. Unstable regime, i.e. alteration of long, relatively quite periods with those of a short-time activation, when the ice velocity sharply increases and the glacier tongue quickly moves down along a valley, is a typical feature of such glaciers. Periods of pulsation of some glaciers vary from several years to up a century and even longer. When surging, ends of such glaciers can advance over many kilometers. The glacier pulsation is relaxation oscillations caused by changes of a force of friction against its bottom and the ice crushing. General indicators of a glacier activation are as follows: changes of a glacier contours and of both its longitudinal and cross-section profiles, a drop-shaped form of its tongue; boundary faults and the ice crushing at the contact with the valley slope; encroachment of a glacier tongue onto other glaciers and slopes; formation of glacier-dammed lakes in lateral valleys, boundary depressions and in places of glacier coalescence. Water of these temporary lakes inevitably rush away and sometimes cause catastrophic glacial landslides. Typical feature of an ice dam is that it moves, floats and melts; so, waters chocked by such dams inevitably break through with time. There are several possible breakthrough mechanisms of such dams: ice deformation under a pressure, a dam buoyancy, formation of crevasses under a stress, formation of over-ice channels under the water running over the dam, formation of intra-ice channels due to mechanical and thermal erosion of water. The last one is probably the mostly widespread. In a case of a pulsing glacier surge, a dangerous reason for the catastrophic floods in mountains can be a breakthrough of waters from the cavities filled with waters within a body the advanced glacier and floatation of the glacier part. This is more rare

but more dangerous case investigated for the first time during a surge of the Kolka Glacier in Caucasus.

1. Particular class of glaciers

Surges of pulsating glaciers are very dangerous in mountains. A surge is a sudden acceleration of glacier flow and it may result in a sudden descent of the end of a glacier, down a valley. There are mentions in literature of such surges in the Alps, as early as the end of the sixteenth century. A prominent description of a Himalayan glacier is given in T. Mayne Reid's (his pseudonym was Charles Beach) novel *Plant Hunters: Adventures among the Himalaya Mountains* (1858). Typical characteristics of surging glaciers are well pronounced oscillations resulting in a re-organization of their dynamic regime and redistribution of their material, without change of their total mass. This dynamic instability is caused by interaction of external factors with rheological properties of glacier ice. A sharp displacement of the glacier body, normally accompanied by advance of its end, is a ***glacier surge***.

Ordinary glaciers are characterized by small changes of their velocity with time (as a rule, these variations do not exceed 50% to 100%), slow fluctuations of the front position with velocities of a few tens of meters per year, and approximate yearly balance between accumulation and ablation in respective areas. This latter is achieved owing to the substance transport between these areas running for time periods of one or a few years. Surging glaciers are distinguished by periodic acceleration of velocity, sometimes by two orders or more, corresponding changes of glacier morphology and structure, and rapid advance of the glacier front over several kilometers, followed by a relatively slow retreat, (but much faster than normal glaciers). Over most of the lifetime of a glacier, its nourishment in the area of accumulation greatly dominates loss of ice from this area by means of its movement, and ice discharge in the ablation area exceeds the ice supply there. Only during a period of surging is the situation reversed, resulting in drastic lowering of the surface in the upper part of the glacier and bulging in its lower part.

Glacier pulsations are relaxation oscillations caused by changes in friction forces against the bottom, and ice crushing. The cycle of pulsations of a given glacier have a fairly constant duration, if external conditions are unchanged, but different glaciers, even in similar geographic situations, can have very different pulsation periodicity. They vary from a few to about a hundred years, but the pattern is frequently broken by climate changes and as a result of changes of glacier morphology, for instance, due to confluence with other glaciers. The time between a surge and completion of the next one is called a ***pulsation period***. It is made up of two phases: surging and restoration. During a ***phase of surging*** relaxation discharge of stresses takes place. These stresses had accumulated on the glacier during the preceding stage of restoration. The glacier is cracked, and velocities of its movement increase by one–two orders and more, resulting in rapid displacement of ice masses from the glacier head to its middle zone and power parts. During this process, the glacier surface is lowered in the head of the pulsing part, while it rises in the middle and lower parts, and the glacier end advances. After the surging stage finishes, the ***restoration stage*** starts when the ice masses are accumulated in the head of the glacier and the front of its activating part gradually moves down.

During the surging stage, the glacier pulsing part, or the whole glacier if the pulsation involves the whole glacier, is divided into two zones: one of outflow and another of evacuation. The ***outflow zone*** is that part of a glacier where ice discharge takes place during surging, and the glacier surface lowers. The ***evacuation zone*** is the lower part of a glacier where the ice mass increases during the surging. Because of the input of ice from the outflow zone, the glacier surface rises, its end bulges and moves down the valley.

During the restoration stage a surging glacier is also divided into two parts, i.e. a zone of growing activity and one of degradation where opposite changes take place. The boundary between them is the ***front of growing activity.*** A ***zone of growing activity*** is the head of the glacier pulsing part where, after the surging is completed, the ice is accumulated, its thickness increases and the velocity of movement accelerates. As the glacier mass grows, the forehead of the glacier activating part (the front of growing activity) moves down the flow, absorbing its degrading part. When the surging finishes, a ***zone of degradation***, i.e. the power part of glacier along its flow, is lacking ice supply from the accumulation area and is destroyed by agents of ablation. Increase of the mass and growth of stresses in the forehead part of the zone of growing activity, in combination with degradation of the glacier end, create conditions for a new surge.

During the surge, the ice velocity and that of the kinematic wave on the glacier sharply increase. Thus, before the surge, the ice motion velocity on the Traleika Glacier (Alaska) amounted to 43 m year^{-1}, and the kinematic wave was 250 m year^{-1}, but at the peak of the glacier surge these velocities increased up to 80-120 and 300-350 m day^{-1}, respectively. Starting at one point on the glacier, a surge spreads up and down, causing displacement of ice mass from the outflow zone from above into the evacuation zone in the lower part of the glacier. As a result, the surface lowers in the upper part, and rises in the lower part of the glacier. A surge of the Steele Glacier in Canada caused surface lowering of 130 m, and one on the Walsh Glacier in Alaska caused lowering of 150 m.

Lowering of the ice surface is followed by a fast longitudinal tension. On normal glaciers, rates of such tension-compression amount to 0.01 year^{-1}. On surging glaciers, during the surges they increase from 0.1 to about 6 year^{-1}. During a surge, values of tangential stress on the bed decrease, together with thickness and inclination. Nevertheless, the motion velocity sharply increases. This may be explained by the very high tension force and abrupt change of rheological properties of glaciers, and/or by conditions of friction on the glacier bed.

During a surge, the upper part of the thickness is broken into vertical blocks (Figure 1), the appearance of which are reminiscent of prismatic structures of lava. These are transformed into pyramids with the onset of melting. Lateral faults appear along the sides, medial moraines bend into loops, and tectonic structures, reflecting sliding along the shear surfaces, are formed. The broken glacier retains its structural features; as takes place in a lava flow, prismatic structures tearing only the surface layer. Invariance of ordering of the structures proves that the glacier's integrity is retained in its core during a surge. During a surge, water discharges are unstable, and often a surge is preceded by turbidity of the water in the glacier river.

Figure 1. Glacier surface during a surge

Fast surges do not always spread over the whole glacier. Movement of glacier tongues most often accelerate, while areas of accumulation above the icefalls remain unchanged. However, some cases are known when the whole glacier, up to its head, was included in a surge (this happened on one of tributaries of the Steele Glacier in Canada), and rarely ice of twinned glaciers is also included into the process. A surge attenuates when ice removal from the outflow zone results in reduction of tensions. After that velocities of the ice movement decrease down to almost zero. Surging is easily recognized on space images—particularly on compound valley glaciers—from loops of medial moraines, bending with the advancing of glacier-tributaries (Figure 2). General symptoms of glacier activation are as follows:

- changes of glacier contours, of both their longitudinal and transversal profiles;
- a drop-shaped form of a tongue or its spreading in the form of an evacuation cone ("a lion paw") (Figure 3);
- presence of ice masses torn away in the immediate vicinity of the glacier tongue:
- evidence of tails of the ice fall along the perimeter of the glacier tongue;
- presence of boundary faults and zones of ice crushing at the contact with the valley slope;
- appearance of great quantities of crevasses and overlapped ice flows on the glacier surface;
- encroachment of glacier tongues onto other glaciers and slopes, and
- formation of glacier-dammed lakes.

Figure 2. Loops of medial moraines on a surging glacier

One of the precursors of a coming glacier surge is change of its surface morphology. Along with a change of forms of the longitudinal and transversal profiles, the first symptom of glacier dynamic instability is appearance of a great number of crevasses and ruptures on its surface. These arise in connection with increase of the ice motion velocity. In this case, transverse crevasses cover the whole width of the glacier, marking zones of tension. As the surge progresses, the system of crevasses spreads over the whole of the mobile part of the glacier. The greatest ice deformation takes place at the end of the glacier tongue, the surface of which is usually a chaotic jumbled heap of ice blocks. As this takes place, the volume of cavities in the glacier body can reach 15-20%. During the culmination phase of a surge, when the glacier is completely trapped by block sliding, large longitudinal faults and zones of ice crushing are formed near the margins of the glacier. Observations of the character and spread of crevasses can indicate not only surging itself, but also the active zones of surging glaciers. One the most easily recognized signs of a glacier surge is change of the pattern of surface moraines, i.e. their shifts, bends, and formation of typical loops (approximate equality of size of moraine loops testifies to the regular periodicity of surges).

Figure 3. "Paw" of the glacier Byrs on the Pamirs during a surge

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Biographical Sketch

Vladimir Mikhailovich Kotlyakov was born in 1931. He is a member of the Russian Academy of Sciences (elected in 1991), and Director of the Institute of Geography, RAS. With particular interest in glaciology and the physical geography of polar and mountain regions, he directed the twenty-year project resulting in the World Atlas of Snow and Ice Resources (published in 1997).

He has participated in many expeditions. He worked and wintered in the Arctic, Antarctica, on the slope of the highest summit of Europe, the Elbrus, and he headed high mountain glaciological expeditions to the Pamirs.

The main theoretical results of his works consist in elucidation of laws of snow and ice accumulation on the Antarctic ice sheet as well as ice sheets in general (1961), the snowiness of the Earth and its fluctuations in time and space (1968), the tasks and abilities of the space glaciology (1973), the application of isotope and geochemical methods to the study of the environment and its evolution (1982), the study of the past four glacial-interglacial cycles (1985 and further on). In recent years, V.M. Kotlyakov has dealt with global changes of the environment, geographical aspects of global and regional ecological problems, and the problems of interaction between Nature and society.

V.M. Kotlyakov is vice-president of the Russian Geographical Society and President of the Glaciological Association. In 1983–87 he was President of the International Commission on Snow and Ice; from 1987 to 1993, he was a member of the Special, and later Scientific, ICSU Committee of the International Geosphere-Biosphere Programme, and from 1988 to 1996, Vice-president of the International Geographical Union. Currently, he is a member of the Earth Council.

V.M. Kotlyakov has been elected a member of Academia Europaea and the Academy of Sciences of Georgia, and an honorary member of the American, Mexican, Italian, Georgian, and Estonian Geographical Societies.