GLACIOLOGICAL PROBLEMS SET BY THE CONTROL OF DANGEROUS LAKES IN CORDILLERA BLANCA, PERU

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Abstract. The retreat of glaciers since 1927 in Cordillera Blanca has produced dangerous lakes at the front of many glaciers. All the known data, most of them unpublished, are reviewed. The known *aluviones* are listed, and those of Chavín, Quebrada Los Cedros and Artesoncocha described in full. In these three cases a breach in the front moraine came from big ice falls into the lake. The protective devices made on the outlets are described, as well as the effects of the big earthquake on 31 May 1970. In the case of Laguna Parón, which keeps its level thanks to infiltrations, the fluctuations of the discharge of the springs as related to the level of the lake from 1955 to 1969 are reported. The projects for lowering the level of Laguna Parón and for emptying Safuna Alta are described. The latter partially emptied in fact by piping after the earthquake, allowing a final solution.

In front of Laguna Parón there is a huge moraine which turns through 90° in the middle of the valley and with a narrow covered glacier on the top. It has been studied by electrical exploration, and using the displacements of 43 marked boulders on the glacier. Assuming a uniform balance on the glacier tongue and semi-elliptical cross-sections, it has been possible to estimate this balance and the glacier thickness. A great amount of the measured velocity comes from the creep of the moraine itself, which seems to be a kind of rock glacier, probably without interstitial ice. It must have taken all the Holocene to be formed. During its complex history a pro-glacial lake must have formed at some time, the rupture of which explains the crooked form.

We explain how preliminary results concerning the internal constitution of the big push moraine at Safuna were obtained in 1967. Cross-sections which were obtained later through electrical and seismic exploration and arduous borings are given. Under the lake Safuna Alta there exists a layer of dead ice which is probably a remnant from an old glacier advance and over which the active glacier slides, but this dead ice does not extend into the push moraine. Since 1950 Safuna Alta has formed, the glacier tongue has lowered by 0.8 m per year on average, and the big push moraine has moved and settled.

The annual balance on the glacier tongue was measured in 1968. It increases by 3.9 m of ice per 100 m in altitude. The discharge of ice near the lake and the annual balance further up-valley allow an estimate of the mean annual balance in the accumulation zone (between 4 850 and 6 020 m) at 2.30 m of water per year. Until now no annual precipitation higher than 1 m/year had been measured in Cordillera Blanca, but this Cordillera includes many meso-climates.

Eight successive moraines are found at Safuna. They are tentatively correlated with the eight existing between Huaraz and Laguna Llaca. Clapperton's "group 4" was not

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formed during the 20th, but during the 17th century. His "group 3" is not from A.D. 1750–1800, but is rather 5 000 to 7 000 years old, according to the offset of Cordillera Blanca great fault.

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EXPERIMENTS ON THE HEAVING FORCE OF FREEZING SOIL

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ABSTRACT. Frost heaving of soil is accompanied by a force which often causes severe damage to structures. It was suggested by Everett that this so-called "heaving force" can be attributed to the coexistence of ice and water in micropores among soil particles which characterize the soil type and can be computed thermodynamically. However, the actual heaving force changes in a complicated manner depending on various factors including freezing speed, constraining condition for a soil block, and, of course, soil type.

Measurements of heaving force were carried out on various soil samples (sand, sandy loam, sandy clay loam, and two kinds of clays) under various freezing conditions: freezing speed in a range from 0.10 cm/h to 0.35 cm/h, presence or absence of water supply, complete or loose axial constraint applied to a soil block. In each experiment, soil was packed in a cylindrical container with a diameter of 11 cm and a height of 10 cm. A disk was placed on top of the soil contained in the container to constrain the sample either rigidly (a complete axial constraint) or less rigidly through a spring (a loose axial constraint). Main results of the measurements were as follows:

(1) Under complete axial constraint, the heaving force decreased with decrease in the freezing speed and with the increase in the size of soil particles (from 6 bars to 1 bar for clay; from 4 bars to 1 bar for sandy clay loam; from 4 bars to 0.8 bar for sandy loam; from 1.5 bars to 0.6 bar for sand).

(2) Without the constraint, the heave amount was almost independent of the freezing speed when there was no water supply (8 mm for clay; 6.5 mm for sandy clay loam; 3.5 mm for sandy loam; 1 mm for sand).

(3) The heaving force decreased very rapidly with the loosening of the axial constraint by weakening the spring.

The results indicate that it is practical to treat the heaving force phenomenologically as a kind of resistive force exerted by freezing soil on a container holding the soil. Because of a volumetric increase due to the transformation of water into ice at the freezing front, both unfrozen and frozen parts of the soil suffer some strain if the soil is somehow constrained by the container. The strains cause stresses which appear as the heaving force. A formula for the heaving force is given in which both the frozen and the unfrozen soil are treated as visco-elastic bodies.

DISCUSSION

R. LIST: What is the porosity of the soil or the saturated water content? Do you get rid of all the air when you let the water into the sample? If you do not, or at least do not vary the air content of the sample, what is the meaning of the experiment?

S. KINOSITA: Referring to our clay samples the water content by weight was 60% to 70%. We did not remove the air from any of our samples before saturating them.