More about severe frost as a triggering agent of microseismic activity in the neighbourhood of large Dam and about the geodynamical conditions leading to it

P. CALOI (*) – M. MIGANI (**) – M. C. SPADEA (*)

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SUMMARY. – In this second note it is evinceneed as the contrast in the rocky-medium downstream and upstream of the Pieve di Cadore dam due to severe frost, is the triggering agent of the microseismicity. The frozen liquid element expansion in the rocky-medium imbued with water downstream of the dam brings out the strains into the medium hidden. Moreover the geodynamical conditions which originate the microshocks are studied, putting forward: 1) the microshocks repeteadly star up during sudden changes of temperature; 2) they especially occur during the few hours of diurnal heating, characterized by a partial surfacial thawing with ensuing abrupt "fall" of the dam downstream. The aforesaid phenomenon represents one of the origin-mechanism of the earthquakes in seismic zones by local strains contrast characterized.

1. – On summarizing in a previous note (¹) the mean behavior of a large dam (particularly of the Pieve di Cadore Dam) within a span of four seasons, the exceptional interest pertaining to periods of severe frost has been revealed for the first time. It could be shown how the medium and the dam are adversely affected by the abnormal behavior of water if temperature falls below zero.

Among the phenomena brought to light that of microseismicity, caused by contrasting strains within the rocky medium upstream

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(*) Istituto Nazionale di Geofisica, Roma.
(**) E.N.E.L. Compartimento di Venezia.

and downstream of the dam and particularly active at the dam bottom, came quite unexpected.

In the previous work special attention was given to the seasonal development of the phenomenon. Here we shall look particularly into its daily course.

2. – To point out this microseismicity we availed ourselves of three seismic stations each of which was installed in underground rooms of centralized control cabin, one on the right hand shore near the dam-top, one in a staple-pit of ashlar Nr XIV (C14) inside the dam (at an hight of 661 m) and one in a staple-pit of ashlar Nr. V (C5), at an hight of 630 m, likewise inside the dam (fig. 1). C14 is in a central position of the dam, C5 is near its left end. The seismographs were of the "Girlanda" type with the same instrumental characteristics except the downstream-upstream (V-M) component of a seismograph installed in C5 whose dynamic magnification prevails over the other two.

Microshocks triggered by frost are recorded by thousands in Winter between December and March when air temperature falls clearly below zero degrees or oscillates widely round it.

Only one series is considered here, recorded between January 1972 and January-February 1973.

As a general feature of the microshocks triggered by the frost it should be observed that as a rule they are recorded *only* by the seismic stations installed within the dam. Recordings are not uniform, however, not even those of the two ashlars; some microshocks could be recorded clearly in C14 and weak in C5, or vice versa, others were delayed in C5 or in C14, still others only in C14 or only in C5. The reason of this unevenneess of recordings may be attributed above all to the different arrangement of the seismic stations, one being located in the central ashlar of the dam (C14), the other in a peripherical ashlar (C5) (fig. 1).

Among the hundreds of microshocks recorded between January 5 and 12, 1972, the one of 23^h12^m of January 7 (fig. 2α) was not recorded in C5. Obviously, the microshock interested more C14 than the underlying rock (as a matter of fact, the high frequency vibrations, peculiar to the latter, are missing): the dam responded first with the uninodal of the ashlar, and then with the fundamental of the entire dam [$T=1.5^s$(3)] which has no appreciable amplitude in C5 as it is near the node.

For the same reasons also the tens of microshocks of fig. 2β do not reach C5.

On the other hand, fig. 2γ shows a microshock which was recorded only in C5: obviously, the perturbation originated at C5 which responded first with its proper uninodal, followed by the higher harmonic of the entire dam ($T = 1^s$ ab.). A similar observation was made for the two microshocks of fig. 2δ (20^h32^m and 21^h34^m of January 8), the second of which was preceded by high frequency vibrations, thus proving the fact that the microshock was also active in the rock below the ashlar.

Fig. 2ε shows two microshocks (the latter, at the 0.5 second's distance ab. was stronger than the former) which originated probably in the rock in contact with C14 which merely reacted to the stress.

Further thousands of microshocks due to frost were recorded in the dam from December 1972 to March 1973.

This extremely numerous series of microshocks, too, featured cases as the above of which we are mentioning here only few.

The microshock of January 8, 1973 (16^h54^m . . .) was recorded much stronger in C5 than in C14 (fig. 3). Moreover, it reached C14 with a delay of about 0,01 sec. This proves that the shock originated near C5.

At 18^h20^m of January 11, 1973 a microshock is recorded both in the dam (figures 4a and 4b) and in the control cabin (figures 4c and 4d), yet with a lower amplitude owing to the lower sensitiveness of the seismographs installed. This is suggestive of the shock originating in the rocky-plain downstream of the dam, as is proved by the lack of proper oscillations of the concrete structure. Other fractures in the rock are those recorded at 19^h20^m of January 12. Their origin was rather close to C14, as proved by the major amplitude observed and by the very short advance if compared to similar recordings made in C5 (fig. 5). The strongest of the two microshocks caused light traces in the control cabin. Another microshock originated in the rock was that of January 13, at 19^h24^m (fig. 6), closer to C14 than to C5. Other examples of microshocks provoked by rock fractures are reported in fig. 7; they had various intensities, although their origin close to C5 appears unique.

The some fifteen microshocks reported in fig. 8, on the other hand, regard almost exclusively the dam and their origin must be sought behind this: the more or less long series of oscillations are animated, in fact, by anomalous dispersion, a striking feature of the dam's free oscillations. They are recorded above all in C14 where the fundamental of the entire dam appears better developped. It is observed that between the beginning of the various perturbations and the beginning of free oscillations of C14 (or of the ones concerning the entire dam) there are different time intervals.

This means that the distance of origin of the various microshocks to the seismic station of C14 varies. The nearest to C14 appears to be, for instance, the one of 18^h47^m of January 26, followed by that of 19^h34^m of January 11; the farthest is apparently that of 20^h46^m of January 26.

Anyway, the order of magnitude of the relative distances may be calculated after the formula (³).

$$v^2 = \frac{\pi}{\sqrt{3}} \sqrt{\frac{E}{\varrho}}\; b \; \frac{1}{T},$$

where v is the propagation velocity of a free oscillation of the period T in an ashlar of the thickness b, $\sqrt{\dfrac{E}{\varrho}}$ indicates the propagation velocity of the dam's proper ordinary longitudinal waves.

For $\sqrt{\dfrac{E}{\varrho}} \approx 4500$ m/sec, $b = 16.5$ m, one gets $v \approx 366 \dfrac{1}{T}$.

Therefore, the velocity results to be inversely proportional to the period of the considered free wave. For a period of $T = 1^s$, one gets, for instance, $v = 366$ m/sec; for $T = 0.6^s$, $v = 470$ m/sec. ab, for $T = 1.5^s$, $v = 300$ m/sec ab.; for $T = 3.0^s$, $v = 210$ m/sec ab. Evidently, these are purely indicative values. With respect to the free wave of about 0.6^s, the second of the above microshocks appears to be, therefore, some one hundred meters farther, with its origin, than the first. The microshock of 20^h46^m of January 26, might have its origin at the plug-bottom, etc.

The microshocks originating near the base of the central ashlar (C14) not only bring about the fundamental oscillations of the entire dam, but often give rise as well to vibrations in the order of about 3^s which may be considered vibrations of the concrete building fixed at one of its ends (the left) and "free" near the plug, always bearing in mind that these are micromovements. The excitation of these oscillations may be more or less retarded: consideration should be given, for instance, to microshocks of figs 9c, 11 (01^h07^m of January 29, 1973), 9b, 9a, 12b, 12a. The microshock appearing in fig. 9c seems to come from right below C14, exactly as the first of fig. 10. At 23^h35^m of January 28 (fig. 11), there was evidently a series of microshocks, as well as at 14^h57^m of January 29 (fig. 9b). The microshock of fig. 11 (at 08^h02^m) evidently took its origin from the rock, even though it extended further to the dam, similarly as the microshock of fig. 12b (01^h49^m) caused successive microfractures in the rock. In fig. 13a (f. in. at 15^h26^m and at 17^h14^m) the vibrations of the dam or its parts, fade in about 4 sec, while in fig. 13b (at 14^h28^m) they develop at distinct intervals and persist for about 50 seconds, which is indicative of the far origin of the microshock (possibly at the plug-bottom).

Among the fractures originating from the rock, that of 14^h22^m of January 29, 1973 (fig. 9a) which was recorded only at C14 and is, hence, very close to this ashlar, deserves attention. Contrary to this, the fracture of January 31 originated on the right side, at two or three hundred metres distance from the control cabin, extending from SW to SSW. Only traces of it could be recorded in C5, fig. 14. Here it should be remembered that the control cabin is separated from the rocky-plain by a gorge of about 120m deep in which the plug fits. Fig. 15 shows a microshock in the rock, recorded merely at C5 and necessarily with its origin rather close to this ashlar, and, moreover, in C5 only the microshocks of fig. 16 are recorded.

3. – Four series of microshocks due to frost have been examined, between January 6 and 12 and between January 15 and 19, 1972: between January 11 and 16 and between January 26 and February 2, 1973. The various thousands of microshocks thus originating were divided into one hour intervals with the first two series, and into two hour intervals with the third and fourth series, as far as their chronological order is concerned.

Fig. 17 refers to the first two series and shows as well the behavior of temperature and of the water-loading moreover the downstream — upstream component (V-M) of the clinographic station installed at the base of C14 of the Pieve di Cadore Dam. Figs 18,19 are referred to the other two series, the first considering temperature, water-loading and clinographic recordings, simultaneously measured at the hights of 682, 660 and 625 metres of C14, the second these same data plus clinographic recordings obtained by the station installed in the rock at 625 ms height in a staple-pit of the right support.

One fact emerges immediately from the figures: the microshocks pertaining to severe frost mass together especially in time periods of sudden temperature changes. Thus, since cooling off requires much more time than warming up, it is in periods of the latter that microshocks occur with maximum frequency. It is not so much the temperature variation in itself which is responsible for microfractures as the rapidity at which it takes place. During the day, provided there is sunshine, temperature recovers what it lost the night before. However, since temperature recovery occurs much faster than losses, during the few hours in which the temperature increases, just then the energy which is capable of bringing in plasto-elastic field breaks, more gathers.

The fact is well outlined also by the clinographic recordings which allow, besides, to define its causes. It is known that the "diurnal wave" following the sun radiations and particularly ample near the dam-top reduces its amplitude as it proceeds toward the dam-bottom where it virtually is annulled. In the Winter months it is strongly reduced also near the dam-top and at last disappears in the period when the sun is low.

At Pieve di Cadore, too, with temperature above zero degrees, the "diurnal wave" at the dam-bottom of 625 ms height is recorded only as a trace, if any. Its behavior in periods of severe frost is altogether different. The rock downstream of the dam imbibed with water swells as it freezes and pushes the dam upstream (M). This is shown by figs 18-21 which reveal also another fact: the contrasting behaviour of the top and the dam-bottom under the *same* acting cause. The sinking of temperature bends the upper part of the dam downstream (V), while the bottom is pushed upstream (M), and viceversa. Successively, when the upper part of the dam, exactly the side opposite the lake, is warmed up by sunniness, bends upstream (M), while at the same time the warmed air partly melts the frozen water within the rocky plain, causing the contraction of the rocky medium with a small downstream (V) bending of the dam bottom. At the lower part of the dam and in periods of severe frost this results in the formation of an *inverted diurnal wave* due to the anomalous behavior of water when the temperature is under zero degrees. The mentioned figures show that for the Pieve di Cadore Dam the height of null rotation is few metres below 660ms where the clinographic component downstream — upstream (V-M) is still, though slightly, in phase with the corresponding component of the dam-top station (682ms).

Coming back to the connecting phenomenon of microfractures, it is observed that during the gradual sinking of temperature below zero degrees the dam is gradually pushed upstream (M) and that only in the sections where cooling is more rapid, this push may bring about microshocks. In other terms, during cooling the medium generally reacts within the plastic field. In the few hours of sunshine, when temperature rapidly recovers what it had lost during the night, the outer part of the medium releases rather suddenly and allows the dam to "fall" downstream (V) (figs. 17-19) in too rapid a way to be contained by the medium within the plastic field. So, after overcoming the strength limit, microshocks occur with higher frequency. As is shown by the clinographic recordings, the deflection described by the dam-bottom, in one way or the opposite way, is more or less the same; however, during the stage of warming up it is covered much quicklier than during the cooling off stage which accounts for the outgrow of the plastic phase and for the following microfractures as a result of a more accentuated momentum.

This phenomenon should be seen as a valuable indication of the mechanism which accompanies seismicity in an area subject to contrasting strains.

The order of magnitude of the stresses sharing with the microfractures rising in the rock can be best valued if one considers that the tangential strains acting downstream at the dam-bottom, the reservoir being completely filled, are about 30 kg/cm^2. These are the forces which act against the medium downstream when, further to the yielding of the rocky system which loses in strength due to partial thawing of the surface, the dam "falls" toward the rocky-plain. But this will be dealt with in detail in another paper.

4. – In order to understand always better the behavior of the Pieve di Cadore Dam closely linked by seasonal variations it was considered helpful to compare the course of temperatures (and of the water-loading) to the simultaneous development of the clinographic recordings taken in C14 at the heights of 682, 660, 625 ms in the months of February and March 1973 which, from the geodynamical viewpoint, are transition months.

At the height of 682 ms, and lesser at 600 ms, the first groups of diurnal waves under the effect of sunniness begin to appear, while the dam starts bending upstream (M), also through the abatement of the water-loading. This behavior continues the whole of March, as far as the height of 660 ms is concerned, and until March 20 for the height of 682ms, the dam-top which beginning at that date starts to bend downstream (V) rather than upstream (M). This anomaly is explained by the behavior of air temperature, which meanwhile is approaching 8-10 °C, and of the water-loading limited to heights below 660 ms. On the reservoir side the part of the dam covered by water has a temperature of about 4 °C which accounts for the upstream pressure of the lower part of the dam up to the said height which has downstream a mean temperature of over 4 °C being reached by the sunniness. From 660 ms upward, however, also the part of the dam on the reservoir side is subject to progressive heating as a consequence of the increase of air temperature, contrary to the submerged part which is governed by a lower temperature. This contrast increases with the height. Thus one has a relative motion of the emerged part contrasting with the submerged part, that is a downstream (V) bending, as is clearly demonstrated by fig. 21. This shows as well the alteration of the diurnal wave as a consequence of the contrasting thermical situation.

At any rate, the behavior of the dam-bottom is much more interesting: in February the above said *inverted diurnal wave* (in opposite phase to that of the top diurnal-wave) continues to develop regularly and with uniform succession (in the mean time the microseismicity due to frost, as shown, starts). In the early part of March, however, with temperature reaching gradually values above zero degrees, the undulation at the height of 625 loses continuously its uniformity of succession, its rhythm is breaking up, and in the second part of the month, when temperature variations are exclusively above zero degrees, it shows only sporadic and irregular perturbations and at the end slackens down into a line without appreciable movements. This means that the outer layer of the rocky-plain is now warmed up above zero degrees and that any valuable contrast against the dam has ceased.

5. – To conclude this note, the interest roused by this particular specimen of investigated microseismicity and by its unexpected origin is underlined. Both have been brought to light through the valuable help of two instruments which already permitted to look into the geodynamical behavior of a large dam and its physical surrounding: the seismograph and the photo-clinograph. The former has revealed the phenomenon, the latter has contributed decisively to its explanation.

Considered individually, the microshocks triggered by the frost are of a very limited intensity (on an average in the order of 10^{10} erg). It should not be overseen, however, that in mountain areas they may originate in time spans of three, four months and by tens of thousands. Since each microshock proves the existence of a microfracture in the rock, with a very slow but continuous weaking of the medium in which the dam has been built.

An intensified, accurate control of the elastic response of the medium — to which the dam is anchored — and of its variations in the time is, therefore, an urgent necessity.

REFERENCES

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