# Microseisms from small closed basins, from inland seas and from the Ocean

P. Caloi – M. Migani

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## 1. Microseisms from the Lake of Pieve di Cadore.

In order to deepen the study of the geodynamic properties of the Pieve di Cadore Dam, it was deemed appropriate to incorporate a seismic station into the dam body.

The station consists of a group of three electromagnetic " Girlanda " seismographs, of the kind of the seismograph installed in the basement of the control Cabin that was built near the dam at the taffrail level.

The new seismic station started its operations early in July 1970 and has already allowed to establish some particular features indicating the behaviour of the dam at given situations. These will be dealt with in this paper.

Particularly interesting proved to be the recordings taken in the dam (fig. 1) during thunderstorms or simple squalls or during the passage of nuclei of cyclones. As early as July 15, 1970 the passage of a depression moving from West toward East caused the station to record microseisms of a short duration (averaging 0.8 sec) and considerable amplitude. One of us has already reported on this fact (³). Here we will consider more specifically that microseismic storm, together with an entire series of other microseisms recordings connected with other transient thunderstorms or with simple passages of microbaric disturbances, of positive phases or not, and loaded with very small amounts of energy.

Fig. 2 shows one moment of the weather situation prevailing on July 15, 1970 when the cyclone, after passing over the Lake of Pieve di Cadore where it caused the recording of very small, but ample microseisms (see fig. 2), in its run toward ESE reached the High Adriatic Sea and caused further microseisms in the Gulf of Trieste which were clearly recorded also at Pieve di Cadore at about 3 hours distance from the recording of the typical microseisms in the lake area (fig. 6). This second, much more energetic microseismic storm, pertaining to the same cyclone, will be referred to more extensively in the 2nd paragraph.

Figures 3 and 4 show the pressure development as recorded at Sant'Angelo (Treviso) and Trieste simultaneous to the passage of the depression. The microseisms in the Pieve di Cadore Lake occur exactly in correspondence to the rapid barographic variations which accompany the restoration of the atmospheric pressure in its positive phase: the first example of sizeable microseisms, associated with rapid variations of pressure in its positive phase, recorded near a very small lake (fig. 5).

There were repetitions of the phenomenon, of course. A cyclonic depression of a much minor intensity than that of July 15, occurred in Venice on September 16, 1970, following the usual West-East direction. Fig. 7 represents the barographic situation at $6^h$ p.m. (Gr).

Fig. 8 represents the development of atmospheric pressure as recorded on the said occasion in Arta Terme, at a few miles distance from Tolmezzo.

When passing over the Pieve di Cadore Lake, the said atmospheric perturbation caused microseisms similar to those of July 15, though of a lesser amplitude due to the lower energy degree of it (fig. 9). This time as well, when reaching the Gulf of Trieste, the cyclone brought about the microseisms peculiar to the Gulf, as witnessed in Padova, Pieve di Cadore, La Maina (figures 27, 9, 26) etc., although its amplituded was clearly lower than that of the July 15 phenomenon for the reasons repeatedly given.

Causing microseisms in the small Lake of Pieve di Cadore, however, does not require the passage of weather perturbations of considerable energy as in the above mentioned case. Even secondary perturbations of a very low energy level are able to cause the recording of appreciable microseisms, such as they happened on July 25, August 3 and 7, 1970 during the passage of low degree barographic perturbations.

It became evident, therefore, that the interaction between air and water, able to cause microseisms from the lake, could have its origin in extremely small energy fluctuations moving on the water.

The recording of such pressure fluctuations required the use of a microbarograph. One bearing the trade mark "Askania" and capable to record pressure variations down to a fraction of 1 Torricelli (= 1 mm Hg) was installed in the control Cabin of the Pieve di Cadore Dam in October, 1970.

The recordings of this instrument gave a full confirmation of our anticipations: the passage of slight microbaric perturbations, both in their positive phase and not, without belonging to squalls or thunderstorms, that is occurring at fine weather conditions, as recorded merely by the microbarograph, is able to cause microseisms which are clearly recorded by the seismic station installed within the dam and, to a lesser degree, by the seismic station of the control Cabin.

The examples obtained are very numerous out of which we are choosing just a few for consideration (figures 10-18).

The interest represented by these recordings is truly strong; we would rather define it exceptional. This is the first time that clear recordings of microseisms are obtained at the margin of a small water basin, and—at the same time—the cause is isolated.

It is to be noted that the microseisms begins and ends with the beginning and the end of the light pressure fluctuations which, through interaction with the lake water, give rise to them (*). Thus there may be microseisms for the duration of half an hour and less, equal to the transition period of the light microbaric impulses from which they arise. If one thinks of the oceanic microseismic storms lasting weeks and weeks, associated with cyclones of high energetic loads which turn the sea and the air upside down, one will understand the interest of microseisms deriving from a small basin, originating from a well defined cause and fulfilling its action in less than an hour. We are thus facing the origin of microseisms, at least of this particular kind.

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(*) It is to be noted that from mid December to about mid March no microseisms are recorded near the Pieve di Cadore Dam in spite of considerable atmospheric perturbations passing by. The simple explanation is that in those months the lake freezes and thus stops any interaction with microbaric perturbations. This proves also that the direct wind action on the dam is not sufficient to bring about microseisms.

Of course, there may be microseismic phenomena lasting several hours, that is as long as the atmospheric pressure fluctuations from which they originate (fig. 18).

It cannot be underlined strong enough that the microseismic storms from the lake usually begin with periods in the order of 3, 4 or 5 seconds and are superimposed by those of a few tenths of seconds' duration. As for the inland seas and oceans (4), local microseisms of various durations may arise according to the different natures of impulses acting in the fluctuations of the atmospheric pressure.

It is observed, at last, that the microseisms from the Lake of Pieve di Cadore must be considered the outcome of forced waves: the very small size of the lake does not allow, in fact, the formation of significant wave systems, so that the building up of conditions for the formation of a cinetic resonance is rather unlikely.

## 2. MICROSEISMS FROM INLAND SEAS.

Let us have another look at the cyclone of July 15, 1970. After having originated the recordings of sizeable microseisms when passing over the Lake of Pieve di Cadore, it gave rise to considerable microseisms, peculiar to the Gulf of Trieste, when it proceeded SE and arrived there (average duration in the order of $2^s,7$), by following the previously examined modalities (3, 4). The microseisms of an energy load clearly superior to that pertaining to those of the Lake of Cadore swing out up to distances of several hundreds of kilometres. However, they do not spread uniformly. Their propagation appears strongly conditioned to the geological nature of the outer layers of the Earth's crust. The microseisms are strongly resumed, for instance, in the Po Valley (recordings of Padova, Bologna and Pavia, see figures 21, 22, 23, where instruments of very small magnification are installed), show normal attenuations toward NW–NE where they arrive, though with strongly reduced amplitudes, until Wien (figures 24 and 25) and find an almost unsurmountable barrage in the Appenine region.

The cyclonic perturbation of September 16, 1970 was of much less intensity. The microseisms that it had caused both at Pieve di Cadore and in the Gulf of Trieste showed, therefore, minor amplitudes (figures 26, 27). Even the extention of the area reached by the Adriatic microseisms appears rather limited as compared with that of the previous perturbation: in fact, the microseisms proved to be already attenuated at Somplago, La Maina and Pieve di Cadore.

The ratio of microseisms amplitudes, measured at the same seismic station at the two above said data, gives a clear idea of the difference of energies which cause the two different cyclonic phenomena.

A closer look at the recordings taken at Pavia on July 15, 1970 (fig. 23) shows us, quite contrary to those of the other stations examined, the presence of microseisms beginning early in the morning with a period of $3^s.3$-$4^s.1$ approximately, which is higher than the microseisms period of the Gulf of Trieste. This apparent anomaly can be explained by observing that as early as July 14 the Ligurian Sea appeared to be hit by cyclonic perturbations.

As already pointed out (3, 4), the seismic station installed along the coastline, at the margin of anyway perturbed sea regions, may well record, during intense perturbations, an entire range of microseisms with periods reaching from the order of 1 sec up to values of the significant coperiodical waves: these are the persistent microseisms of maximum amplitudes which reach major distances. The others, of a sporadic nature, are associated to systems of temporary waves of a low energy load. The recordings, for instance, taken by the Genoa seismic station on the said day and the next day (figs. 28-30), showed microseisms of a chaotic aspect, as was proved by the simultaneous recording of a wide range of oscillations pertaining to the sea struck by cyclonic perturbations. Of these numerous oscillations only those with periods in the order of 3,5-4 sec reached Pavia beginning at $9^h$ a.m. of July 15 where they are recorded at regular intervals. They represent the persistent microseisms arising in the Ligurian Sea and pertaining to the coperiodical significant sea waves. Seismographs of equal properties did not record in Bologna those rather attenuated microseisms, although their distance from the Tyrrhenian coast is not much longer than the distance to Pavia. This means that while the microseisms from the Ligurian Sea find an outlet between the Alps and the Appenines which allows them to reach out toward the higher Po Valley, the Appenine range forms a sort of barrage hampering the propagation toward the rest of the Po Valley (fig. 31).

At about $7^h$ p.m. of July 15, 1970 the microseisms coming from the Gulf of Genoa were overlapped in Pavia by those coming from the Adriatic Sea. They presented periods in the order of $2^s,7$ and small amplitudes. Pavia must be, therefore, particularly sensitive to microseisms caused by perturbations of the Ligurian Sea.

2.1. This distinction between persistent microseimss deriving from different origin centres, is made possible by the fact that there is no dispersion in the propagation of microseisms (3, 4).

The perturbation which gave origin to the microseismic storm in the Ligurian Sea, continued its course down the Tyrrhenian Sea and caused the recording of sporadic and persistent microseisms also in the Seismic Station of the University City of Rome (fig. 31).

It is interesting to observe the difference of recordings of microseisms as they were made simultaneously in Genoa and Rome during the passage of the said storm. In Genoa the microseismic agitation reaches its peak intensity between approximately $1^h$ p.m. and $10^h$ p.m. hours (Greenwich Mean Time) and is of an exclusively local nature: its chaotic aspect (figs. 28-30) denotes the overlapping of oscillations from sporadic, temporary wave systems: in fact, the pseudo-periods do not exceed 3 sec.

In Rome appreciable microseisms set in toward $3^h$ p.m. of July 15. They increase gradually in amplitude and reach peak values toward $4^h$ p.m. of July 16, and later. The time difference is only apparent, however. It is to be noticed that in Rome the microseisms present periods in the order of 4-5 seconds against the average 2 seconds of Genoa. The explanation will be found in the instruments used. The Genoa short period installations have dynamic magnification varying on an average from 8.000 to 3.500 for periods between 1 and 3 seconds, while the dynamic magnification of movements with periods from 4 to 5 seconds decreases from 600 to 300 (1).

The possible presence of microseisms with higher than 4 sec periods in Genoa is therefore generally camouflaged by shorter period perturbations of a local nature which are amplified some ten times and more. The Galitzin-Wilip seismographs installed in the Seismic Station of the University City of Rome present opposite features, that is a small magnification for short periods

(400-600 for periods from 1 to 2 sec) and magnification in the order of 1500 for periods between 4 and 5 sec.

In our belief the microseisms having periods from 4 to 5 sec take their origin from a large marine area between the islands of Capraia and Elba and Livorno. This area features small sea depths and is limited in such as way as to form something similar to an ample gulf (fig. 32) for perturbations coming from NW and favours the building up of dynamic conditions able to exalt the formation of microseisms (4). We think that in that area the significant waves may reach in their full development 4-5 sec and cause on the sea bottom the formation of coperiodical microseisms as they are recorded in Rome.

For the above reasons the said microseisms are usually not observed at all in Genoa, except in cases when they are of considerable amplitudes and the local agitation is of a small scale (upper part of fig. 30); however, as soon as the local agitation is rising, any trace of microseisms of about 5 sec disappears in Genoa (fig. 30), while at the same time they are recorded in Rome.

The period increase from 4 to 5 sec approximately is not due to a phenomenon of dispersion (which—as we know—is almost inexisting with microseisms), but to the period increase of the significant sea wave system from which the microseisms originate. This is true when the microseismic storm exceeds certain duration limits (2). It is a different way of expressing the repeatedly presented idea: the period of microseisms increases until it reaches the maximum value when the system of significant waves reaches its full development.

Concerning the relation between the period of sea waves and the period of microseisms it may be observed that the periods of the liquid wave and of the solid wave coincide in the case of waves which " feel the bottom ", while in deep waters the bottom effect causes the period of the acting sea wave to be reduced to half its value, following the theory of Longuet-Higgins.

## 3. MICROSEISMS FROM THE ATLANTIC OCEAN.

We are adding here few words to what has already been written by one of us (4). The microseisms of Atlantic origin derive from the passage of vast depression areas from West to East which in the neighbourhood of the European coast interact with the ocean water below them. The high rate periods (7-9 sec) find their explanation in the formation of extensive fetches in which the significant waves can reach their complete development. In correspondence with them arise microseisms of equal periods on the bottom. The exaltation of these microseisms may be attributed to phenomena of cinetic resonance among the significant waves and coperiodal barographic fluctuations in the positive phase which are present in the atmospheric pressure (4).

Of course, also in the Atlantic origin areas the manifold local wave movement causes a wide range of microseismic perturbations near the coasts which are capable of covering up even the persistent microseisms of higher periods (fig. 36). However, after a short distance from the origin areas only the latter continue to propagate and may even reach out to few thousand miles. The others, the microseisms originating from sporadic, temporary wave systems are more or less rapidly absorbed by the medium, the more rapidly, the higher their frequency (4).

Contrary to what happens with fundamental microseisms originating in inland seas, the continental mountain systems do not constitute unsurmountable obstacles to the propagation of Atlantic microseisms with maximum period. Though subjected to various attenuations in the various directions, they are recorded everywhere in Europe, even at few thousand miles' distance from their origin area.

3.1. We are giving two significant examples of Atlantic microseismic storms.

It was on January 19 and 20, 1971, with a depression in course off the Scandinavian coasts which gave rise to microseisms peculiar of the seas of this area, with periods of about 6 sec, and widely recorded, for instance at Uppsala (fig. 33). During the first hours of January 20 a perturbation proceeds from the North Atlantic Region toward the British Isles (figs. 34-35). Its center is not far from Ireland at midday of January 20 and reaches her at $6^h$ p.m. of the same day. This extended perturbation gives rise to significant wave systems to which correspond microseisms of considerable amplitude and periods of about 8 sec. These are the fundamental microseisms of the area. They are bound to systems of significant waves and have reached their full development (4). They are recorded with high amplitudes by all seismic stations equipped with medium and long period seismographs: Oporto (fig. 36), Toledo (fig. 38), Rome (fig. 37) etc. In the Scandinavian seismic stations, too, the local microseismic storm, bound to the perturbation more in the North, is gradually superseded by the one associated to the perturbation off the British Isles (for instance Uppsala, fig. 39) for all the day (January 21). In the meantime the formation of a perturbation in the High Tyrrhenian Sea causes a local microseismic storm which in Rome overlaps the Atlantic one (fig. 37).

Another considerable Atlantic microseismic storm took place in mid February 1971. A vast cyclonic area extends at midday of February 13 between Iceland and Norway (fig. 40). The microseisms show a mixed aspect in Scandinavia: at Uppsala the oscillation groups with periods in the order of 6 sec, peculiar to the microseisms arising in the sea strip opposite Scandinavia, alternate with oscillation groups having periods in the order of 8 sec and which are peculiar to the microseisms of the Atlantic area off the British Isles. The latter are quite more ample (fig. 41). The major distances are reached, however, as usually, only by microseisms of 8 sec periods (Rome, University City, fig. 43). In the course of further developments of the weather situation the cyclone area shifts toward SW, hitting progressively and exclusively the British Isles (fig. 44-45). At Uppsala, the microseismic " Scandinavian " agitation is simultaneously attenuating gradually, but the one of a clear Atlantic origin emphasizes itself more and more and at last prevails almost exclusively (fig. 42).

For the repeatedly stated reasons, also the Scandinavian seismic stations (Uppsala, Umea, etc.) of short peculiar periods do not record microseisms with periods higher than 4-5 sec. As anywhere else, the instruments of one's own short periods record disorderly impulses under strong microseismic storms in which the periods from 2 to 3 seconds prevail, peculiar to local perturbations (Baltic Sea, Gulf of Bothnia).

## 4. Conclusions.

*a)* The paper emphasizes the exceptional interest raised by microseisms deriving from the small artificial lake of Pieve di Cadore, caused by interaction between the lake water and the fluctuations of atmospheric pressure, in the positive phase or not, passing over the lake. The active fluctuations may be of negligible size (fractions of Torr.). They are particularly active when connected to increasing pressures.

The periods of these microseisms are generally less than 1 sec and subside very quickly. Frequently a simultaneous origin (or even a precedente) of longer period microseisms up to 4-5 seconds is noticed.

*b)* The microseisms coming from inland seas may locally present a wide range of periods, from less than 1 sec to maximum periods, caused by coperiodal significant waves peculiar to the sea area where the microseisms take their origin. Only the latter prove to be persistent and apt to propagate over distances of few hundred miles. The Gulf of Trieste gives rise to persistent microseisms with periods in the order of 3 sec, while from the sea area North of Elba Island derive persistent microseisms having periods from 4 to 5 sec approximately. Seismic stations sufficiently remote from the origin areas record only persistent microseisms: since microseisms are not subject to appreciable dispersion, their period is apt to reveal the origin area.

Microseisms from inland seas find their propagation hampered in correspondence to mountain systems. The Appenine Range, for example, constitutes a kind of barrage thwarting the propagation of microseisms from the Gulf of Venice; these are favoured, however, by the Po Valley. The microseisms from the Tyrrhenian sea, too, are strongly reduced by the Appenines, while the microseisms originating in the Gulf of Genoa propagate toward the higher Po Valley through the « window » between the Alps and Appenines; between the Colle di Cadibona and the Passo dei Giovi.

*c)* The same mechanism used to explain the origin of microseisms from closed basins or from inland seas is as well valid for microseismic storms of oceanic origin: an interaction between atmosphere and hydrosphere. The vast oceanic extensions and the duration of cyclonic perturbations permit the formation of extensive fetches in which the significant waves may reach their maximum development: this explains the high period of persistent microseisms of oceanic origin (5-6 seconds for the vast Atlantic depressions from the Gulf of Biscay to the British Isles and beyond). The more developed microseisms arise generally not far from the coasts, due to waves " feeling the bottom " when the pressure fluctuations in the positive phase interact with the underlying coperiodal significant waves.

The microseisms of oceanic origin can propagate over several thousand miles distances from the origin area, within the continents, without suffering strong attenuations by mountain systems. This must be attributed both to the major energy load transferred to the bottom in the interaction air-water, and to the higher wave length which—contrary to microseisms from inland seas—allows them to reach larger thicknesses of the Earth's crust.

Of course, in the oceanic coasting zones, too, near the origin areas of the microseisms, seismograms generally present a chaotic aspect due to the overlapping of microseisms associated with systems of temporary, sporadic sea waves whose periods are lower than that of the microseisms caused by the significant waves. It is only the latter which remain out of a variable radius area, which is limited in any case, and propagate up to maximum distances maintaining their original period.

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