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Geognostic investigation into the danger recognition of San Lugano Pass (Bolzano-Italy) – Sinkholes in the Bellerophon gypsum

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1 INTRODUCTION

The phenomenon of “karstic sinking” or “sinkhole” resulted as not diffused in the Alto Adige area, but has been detected, generated by natural causes, only in restricted areas near San Lugano (Trodena – BZ).

The studied area is situated in the south west of Bolzano, on the southern slope of Torlago Mount, in a turistical access area to some main skiing and naturalistic resorts of the Trentino-Alto Adige like Val di Fassa and Val di Fiemme.

The studied area is situated in the Maso Scofa locality, at the hydrographic right side of the valley, nearly in the middle of the slope.

Maso Sofa locality is constituted by three habitations, including nearly fifteen people, a big stable for cattle shelter and lands for grazing and cultivations which surround the area for at least two kilometers.

This area has been interested in the past (oral witnesses over the past two centuries) by other similar collapses situated in the area of an abandoned gypsum quarry.

Due to the many cultivation activities, it is impossible to recognize the ancient excavations.

During the autumn 2000, because of intensive and extensive rainfalls, another super-

ficial collapse of large dimensions occurred. In the meadow land near Maso Scofa habitations, a cone shaped abyss has opened with a diameter of nearly 8-10m, and 15m deep.The position of this instability is very close to the civil habitations, in an area very close to the cattle grazing land and houses. The risk for resident people and animals is extremely elevated.

In order to determine the problematics which are linked to such a phenomenon, which has never been previously studied or known, except by the residents, a detailed geological investigation was carried out in 2001-2002 according to a geomorphological survey and a wide geognostic field research.

This area is characterized by a very complex stratigraphic and geostructural situation, of difficult interpretation due to the presence of important detritic and morenic covers as well as regional faults.

1 2 GEOLOGICAL – GEOMORPHOLOGICAL FRAMEWORK

The examined area is situated at the limit with the Atesine volcanic rocks. Some outcropping sedimentary permo-triassic formations have been surveyed. Due to the rarity of rock outcrops and predominance of sedimentary cover, the underground reconstruction is extremely difficult (Fig. 1 – Geological and Geomorphological maps).

FIGURE 1: Geological and Geomorphological map.

2.1 Stratigraphic outline

The reconstruction of the stratigraphic sequence has been the result of detailed field surveys as well as direct investigations. The geological characterization of the litholgies was based on the bibliographic notes of the Predazzo Geological Map 1:25.000 as well as on the field surveys.

The detected lithologies are the following ones:

Atesine volcanic rocks (Permian):

Rhyolithic homogeneous red/brown red coloured volcanic rocks, constituted by massive rocks which are interested by an evident subvertical fracturation. In S. Lugano area the ignimbritic formations assume a breccia aspect due to the presence of some brown glassy levels.

The ignimbrites have been detected in the downslope of the area, and are characterized by the presence of three discontinuity systems which can be connected to the Linea Trodena discontinuity.

The joints spacing havs a range from 10 to 50 cm with metric persistances.

Val Gardena sandsones (Middle Permian):

Arenaceous complex with variable granulometry. The sandstones are discordant on the volcanic formations which mainly constitute the provenance material. In the studied area the detected sandstones are in continuity with the volcanic south eastern rocks, characterized by a coarse granulometry, brown red coloured, with frequent alterations.

Bellerophon formation (Upper Permian):

This geological formation is at the limit with Val Gardena Sandstones and is constituted by an alternation of silty marls or sandstones with frequent gypsum nodules and lents of variable thickness. The outcrops are present in the northern abandoned quarry area and on the slope below Maso Scofa habitations. In the studied area this formation is constituted by sandstone and gypsum level alternations. The sandstone levels are red formations which can be alternated or massive. The gypseous levels are characterized by grey folded material with high alteration.

The surveys which have been carried out on the two outcrops evidenced a nearly constant layer joint trend which is characterized by a medium azimuthal dip of N340˚-20˚, a variable spacing from 30 to 100 cm, and a high persistance. The joints surfaces are undulated-rough, mostly opened.

Two discontinuity systems have been detected, nearly parallel to two tectonic main directions, with medium-low persistance.

Werfen formation (Lower Triassic):

Thickly bedded formation, composed of many strata: marly limestones, silty limestones, siltstones, sandstones, gypsum. A particular member of this formation has been recognized: the Mazzin Member which is constituted by micritic marly limestones, of green/gray colour, outcropping in the backslope of Maso Scofa locality. A geological field survey detected a joint dip which resulted to be in corrispondence with what has been measured in Belleorophon formation.

Detrital deposits and undifferenciated till (Quaternary):

Loose deposits are involved in the whole studied area. Particularly some scree slopes and colluvial scree slopes have been detected at the bottom of the rocky scarps. Flat or gentle slopes are covered by till deposits which are constituted by:

- angular fragments, mainly of ignimbritic origin, with the presence of sandstone fragments and gypsum fragments in minor quantity,

- an abundant terrigenous dark brown coloured matrix.

2.2 Tectonic outline

The southeastern area of Bolzano belongs to an area of tectonic junction between the Atesina Plateform to which it belongs, and the Dolomitic area of Southern Alps.

The most important tectonic element is represented by Trodena Line which has a regional character and NE-SW direction.

Trodena Line is a reverse fault with an uplift of its South western side and a throw increasing from SW to NE until Curia, then decreasing and disappearing near Rocca. This important structure continues in the North Eastern direction and its direction changes completely following the E-W direction of the Occidental Dolomites axis. Trodena Line presents in this area many other minor structures which keep the main fault characteristics, lowering its South Eastern side.

Stava Line and Solaioli Line are other main tectonic structures, and are characterized by a sequence of E-W dislocations which constitute the North-Western termination of the tectonic elements situated in the Eastern side of the studied area. It is important to underline that such structures are also subparallel to the terminal side of Trodena Line, nearly E-W. Maso Scofia surroundings result to belong to an area which is characterized by some important tectonic features.

In particular, from the seismic and geognostic drilling investigations a NE-SW fault has been detected, parallel to the Trodena Line, and can be probably considered as a secondary structure of the considered Line.

This fault is responsible for the contact between the Ignimbrites and Val Gardena Sandstones, lowering the oriental portion and presenting a behaviour which is similar to the main Line.

Other important faults follow an E-W direction, and are connected with the Stava Line; one is situated in the North side of the studied area nearly at the base of the ignimbritic slopes which close the mountainside, the other one in the southern area very close to the houses in correspondence of the old quarry. These structures are responsible of an uplifted wedge, which is recent compared to the surrounding volcanic rocks. The lower limit probably sets up on the Bellerophon gypsum layers which can be also deformed.

2.2 Hydrogeological outline

The studied area is characterized by a poor rill and a moderate hydrographic grid, in spite of the presence of many valley relics. This situation is probably due to the effective infiltration in the first underground metres which are characterized by the presence of porous material;in this case the groundwater discharge is karstic and probably occurs following the direction NNE-SSW which is also the direction of watersheds and superficial small valleys. During the field investigations only one poor superficial rill has been detected, due to meteoric events, near the brook which is situated at the eastern side of the examined area. Other very scarce hydrological outflows, have been detected at an altitude of 1150 m.o.s.l. at the level of the Bellerophon Formation outcrop. During the geognostic borehole drilling investigations a small groundwater table has been detected inside the ignimbritic body situated in the Southern part of the considered area.

From a Geochemical point of view, some important quantities of dissolved salts have been detected in the groundwaters which can be intercepted at the base of the mountainside, after having been in contact with the stratigraphic sequence which has been just described. Such a situation reflects the high solubility of the bedrocks.

2.2 Geomorphological outline

The glacial erosion is at the origin of the undifferenciated tilt deposits which are present on most of the mountainside and represents one of the most characteristic element of the past geomorphology in San Lugano Valley. Afterwards, other erosion features occurred along the tectonic structures and modified the geomorphological outline of the examined mountainside, especially karstic and gravitative erosion.

The karstic erosion is one particular important factor for this investigation, and is characterized by the presence of:

- many relic valleys,

- numerous dolines on the slope below the houses,

- wide circular morphologies above Maso Scofa and at the level of the Eastern grassy area (Fig.1).

The karstic modelling is also underlined by other geomorphological elements like the presence of:

- dolines in the grassy area in front of the houses (Fig.1),
- the flat shape of the terrace on which is located Maso Scofa,

- the presence of small depressions, around 2 m of diameter and subcircular, which

have been detected in the wood wich is situated in the eastern part of the studied area.

The nature and solubility of the bedrock is at the origin of the landscape evolution due to karstic erosion.

In this area many factors can be responsible of such a process, the most important one is the high solubility of the evaporitic rocks, which is supported by the carbon dioxide enrichment in the meteoric waters. This enrichment is due to the presence of agricultural soils as well as the low temperatures persisting most of the year.

At the present time the karstic macroshape which is interesting the investigated area is the sinkhole, which formed during the autumn 2000 in the grassy area in front of Maso Scofa. The sinkhole had a diameter of nearly 8-10m, and was 15m deep, with a typical morphology of karstic macro-events, like the perfectly circular shape of its diameter. This structure is due to the collapse of the roof of underground hollows or to the dissolution of thick soluble rock layers. These events can be observed at the surface as closed depressions highly deepened towards the central area, and with a diameter which is inferior respect to the whole depth.

Particularly:

- the event occurred after an intensive rainy period,
- the event occurred without any evident warning signals,
- no collapse signs have been surveyed on the ground around the break limit,
- the sinking occurred during the night and the inhabitants of the nearest houses heard only a strong rumble.

There is an evident analogy between the tectonic and geomorphological outlines. The axis of ancient and recent sinkholes is parallel to the NE-SW tectonic system direction, and probably corresponds to a fault system through which the water infiltration can be favoured.

2 3 GEOGNOSTIC INVESTIGATIONS

In order to examine the underground stratigraphic sequence as well as to detect other eventual cavities, the following direct and undirect investigations were carried out:

1. Geological and geomorphological detailed field survey.

2. N.2 electric tomography sections.
3. N.2 continuous logging borehole drillings.
4. N.12 seismic refraction sections.
5. N.7 destruction borehole drillings.
6. Microgravimetric survey.
7. N.2 continuous logging borehole drillings.

3.1 Geognostic borehole drillings

With the data issued from the destruction borehole drillings it has been possible to survey the bedrock surface, which corresponds to the ancient buried karstic morphologies. It has also been possible to localize the gypsum levels which are 12 m thick in the north western area, but strongly reduced to decimetric thicknesses and intercalated in the sandstones in the south eastern area. Using 3D models it has been possible to get the interpretation of these unconformities.

Other results issued from these investigations are referred to a clayey layer in corrispondence with the NE-SW fault area and the underground complex stratigraphic situation.

From the observation of the material issued from the borehole drillings it has been possible to get the following results:

- SD1: m. 0.00 ? m.11.00: Detritic cover.

m. 11.00 ? e.p.(end perforation): Ignimbritic bedrock which is the seat of a small groundwater shed.

- SD2: m. 0.00 ? m.7.50: Loose deposits.

m. 7.50 ? e.p.: Reddish sandstones with scarce gypsum thin layers. The sandstones are slightly compact or completely weathered.

- SD3: m. 0.00 ? e.p.: Loose deposits. The presence of a thick reddish clayey layer has been detected, which probably corresponds to the NE-SW fault cataclastic zone, completely argillated and alterated, also surveyed by the Geoelectric Investigation.

- SD4: m. 0.00 ? m.7.00: Loose deposits.

m. 7.00 ? m.22.00: Completely weathered sandstones and often reduced to sand.

m. 22.00 ÷ m.25.50: Total or partial cavity (22-24 m.).

m. 25.50 ? e.p: Sandstone bedrock of medium competence. This borehole drilling is very relevant as it represents the only documentation of a probable cavity.

- SD5: m. 0.00 ? m.5.00: Loose deposits.

m. 5.00 ? m.14.00: Alternation of gypsum and sandstones of low competence.

m. 14.00 ? m.25.00: Gypsum. This level can be correlated to the gypsum vein which is quarried in the neighbourhood.

- SD6: m. 0.00 ? m.9.50: Loose deposits.

m. 9.50 ? m.15.50: Gypsum.

m. 15.50 ? e.p.: Sandstone bedrock with low-medium competence.

- SD7: m. 0.00 ? m.24.00: Thick detritic layer.

m. 24.00 ? e.p.: Highly weathered sandstone.

These borehole drillings resulted to be very relevant for the detection of a probable underground cavity, the description of a complex geology for the examined area, and for the surveying of gypsum lens with significative thickness.

Through the results of the continuous logging borehole drillings it has been possible to detect the presence of arenaceous and gypsum material completely dissolved and reduced to sand, which probably reflects the presence of karstic embryonal cavities. These cavities have beeen surveyed in the eastern-south eastern area of the country houses, at depths between 20 and 24 m.

The results also evidenced some small water infiltrations concerning mainly the gypsum levels, with a consequent support to dissolution processess.

- S1: m. 0.00 ? m.14.00: Loose deposits.

m. 14.00 ? m.17.00: Bedrock superficial alteration.

m. 17.00 ? m.20.00: Reddish sandstone highly weathered by water, alterated, fractured and softened, with the presence of a green weathering patina.

- S2: m. 0.00 ? m.8.00: Gravelly with sandy-silty matrix level.

m. 8.00 ? m.16.50: Weakness zone constituted by weathering sandstones derived sands, rocks fragments and totally fragmentated portions.

m. 16.50 ? m.22.50: Reddish sandstones with gypsum thin layers of around 2cm thickness.

m. 22.50 ? m.25.00: Reddish sand produced by the sandstones weathering and total gypsum dissolution, corresponding to probable karstic embryonal cavities.

At the end of the borehole drilling a small water infiltration was detected.

- S3: m. 0.00 ? m.8.00: Detritic material with the presence of some ignimbritic erratic coarse boulders.

m. 8.00 ? e.p.: Compact to fractured reddish sandstones.

From m. 21,00 to m. 24,00 the core has not been recovered, but the video-camera survey could confirm the presence of gypsum with small water infiltrations.

- S4: m. 0.00 ? m.9.50: Loose deposits.

m. 9.50 ? e.p.: Fractured to compact weathered sanstones.

It has been possible to survey the presence of karstic embryonal cavities in connection with the present gypsum dissolution phenomenon, as well as with the presence of 3-4 m thick portions of totally weathered-softened-reduced to sand material.

3.2 Geophysical investigation

The geophysical survey has been carried out using the refraction methodology. A less resistant ogival shaped zone has been detected, and corresponds to the area in front of the farm, at 15m. u.g.l. This investigation has been confirmed by the weakness area which has been found by S2 borehole drilling.

The geoelctrical profiles have also detected the presence of a SE-SW fault which has been confirmed by the borehole drilling SD3.

The geophysical investigation could have given better information, but the results have been limited by the important detrital cover thickness, the geological complexity and the presence of high voltage electric wires.

3.3 Microgravimetric investigation

With the microgravimetric survey it has been possible to detect two areas which are characterized by the possible presence of buried cavities, located in the south eastern area of the country houses, partially observed on SD4 borehole drilling.

This investigation could not give any other new information on the underground knowledge. This is probably due to the depths limits of such a methodology, as the necessary information should concern dephts below 20m u.g.l.

3.4 Geochemical investigation

During the geological-geomorphological surveys, many water inflows have been detected, and most of them have been intercepted by the inhabitants for irrigation purposes. These water inflows are mainly seasonal, connected to the superficial waters infiltration processes due to intense precipitations, and less frequently the origin can be permanent springs characterized by a low flow rate which have been documented during the years by the Maso Scofa inhabitants.

In the examined area, 9 water inflows have been surveyed, but only 4 of them have been sampled and analyzed as they have resulted to be more relevant or close to the studied area.

P1, P2, P3 and P4 water springs have been sampled and analyzed.

The other 5 water spings are here below described:

NOT ANALYZED WATER SPRINGS

P5 is located 60m above the P1 spring and is characterized by a flow rate of 500l/day.

P6 is “Sorgente Loca”, is located far and to the east of Maso Scofa and is characterized by a very dirty and ferruginous water, with an assesed flow rate around 100l/day.

P7 is “Val Molini” spring which is used for San Lugano aqueduct.

P8 is a seasonal spring situated 150m to the north of of Maso Scofa.

P9 is in the western area of Maso Scofa.

ANALYZED WATER SPRINGS

P1 is used for cattle drinking and is situated 150m to the south-east of the wide depressed area in the neighborhood of Maso Scofa. This spring is highly seosonal and is influenced by the rains, then is characterized by dry or frosted periods. The geochemical analysis has confirmed the direct provenance from rain, with a circulation inside the Atesine volcanic rocks. The SiO_2 concentration resulted to be of 13.2mg/l. Other salt minerals resulted to be in low concentrations as sulphates (5mg/l). The hardness resulted to be of 2˚F.

P2 spring water comes from the ignimbritic bedrock, with seasonal changes with a medium flow rate and during alimentation periods the yield is of 10l/min.

From the geochemical analysis the water resulted to be classified as medium-mineral in the calcic bicarbonate facies. This water flows through limestone formations (Werfen) as well as through Atesine volcanic rocks. This has been confirmed from the geochemical analyses from which results a HCO_3 concentration of 405mg/l and a SiO_2 concentration of 12,1mg/l. In this water are also contained other relevant mineral salts quantities, as calcium, iron, magnesium and nitrates. The hardness resulted to be of 36˚F.

This medium-high mineralization could be explained by the proximity or interaction with a fault area.

P3 is “Busa Piccola” spring. It is a permanent spring with a low flow rate and is situated close and to the north-west of Maso Scofa. This spring was previously used for the daily supplies of the farm inhabitants, at present only for agricultural purpses.

The water results to be oligomineral with a calcic bicarbonate facies, flowing through the Atesine volcanic rocks. The SiO_2 concentraton resulted to be of 11,8mg/l, other minerals content is very low due to the very short residence time.

P4 is “Nasa” spring and is responsible of a small bog or hydric stagnation, and it is located below the old gypsum quarry area to the south of Maso Scofa.

From the geochemical analysis the sulpahtes concentration resulted to be very high, 1170mg/l, exceeding the limit of water drinkableness. The salt minerals concentraton is very high and close to the sulphates saturation limit, indicating a long residence time in the Bellerophon Formation.

The calcium, sodium, magnesium and iron concentrations resulted to be elevated.

High concentraton of calcium, sulphates, magnesium and iron resulted from the chemical analysis, with a total hardness of 56˚F.

This water composition is characteristic of gypsum interaction.

Through the water geochemical analysis it has been possible to show that the groundwater circulation on the slope above the farm is characterized by short residence times and directly connected to the rainfalls, giving an oligomineral character to all surveyed waters.

On the slope below the farm, the waters show high concentrations of dissolved salt minerals, because of the interaction of waters with the Bellerophon Formation and long residence times in the gypsum. This factor has a negative influence on the stability conditions, as it enables the gypsum solubility then the formation of embryonic karstic cavities.

This geochemical survey has been relevant for the monitoring of groundwaters which can be processed by the assessment of dissolved minerals and sulphates concentrations.

3 4 SUMMARIZING RESULTS OF THE GEOGNOSTIC INVESTIGATIONS

Through the geognostic investigations it has been possible to detect the presence of the embryonic cavities or possible underground empty zones in the SE area to the buildings, as well as the following local geological pecularities which can be also connected to the sinkholes events:

- The presence of gypsum thick layers, which can reach 10m, in corrispondence with the northern grassy area, on the slope above the houses (Fig. 2).
- The thick gypsum layers do not present important sedimetary covers, then their dissolution cannot be balanced by a thick arenaceous lithoid roof. As it has been observed in SD5, the gypsum lents are directly covered by loose sediments over 5m thick.This situation is probably at the origin of sinking.
- The main gypsum layer probably continues from the old quarry in the direction of the country houses.
- The karstic macrostructures show a NE-SW oriented direction which is parallel to the Trodena Line.

FIGURE 2: Tridimensional Model of the underground**.**

Using these data a Local Riskiness Map was processed.

The following factors were considered for the elaboration:

1. The presence of thick underground gypsum layers,

2. Their proximity with the ground level,

3. Their proximity with the houses,

4. The presence of a lithoid cover with medim competence, between the gypsum layers and the loose superficial deposits.

In synthesis the Riskiness Map is based on few basic criteria, one of which consisting in the determination of riskiness high intensity areas where thick gypsum layers have been detected. With return times superior to 100 years, the probability of sinkoles occurrence may increase consequently with the washout facility and karstic concentrated erosion.

The riskiness intensity mainly decreases in the areas which are distant from the houses, where the bedrock is massive, and where gypsum levels are absent.

From the Local Riskiness Map the more risky areas resulted to be the following ones:

1. the northwestern area of the old farm,
2. the southeastern area of the whole residential complex.

At last, from the tridimensional model representing the limit between the bedrock and the loose material cover (Fig.2), a wide morphology similar to a doline or sinkhole has been determined in the area to the SE of the houses. This can be probably due to a relic karstic phenomenon partially obliterated from recent natural or anthropogenic sedimentary covers. From the observations of SD4 borehole drilling, the probable undergroud cavity could represent some collapsed and not completetly filled up zones, in corrispondence of this area which has been defined as with the higher risk, from all the direct and undirect surveys.

4 5 INTERVENTION AND MONITORING SYSTEM PROPOSALS

The following intervention works concerned the sinkhole which occurred during the Autumn 2000:

- Filling with good geotechnical and permeability characteristics material.
- Superficial covering using a clayey-impermeabile layer in order to prevent any concentrated water infiltrations in corrispondence of the collapse area.

The areas which can be considered as highly risky by the Local Riskiness Map, with the areas where embryonic karstic cavities or partial cavities have been recognized, will be monitored in order to assess during the time any variations of the system and to find the solution.