Geotechnical characterization of conglomerate formation for Koysha dam, Ethiopia

Giuseppe Pittalis **Andrea Deliso** **Claudio Rossini** **Vincenzo Millesi**

Studio Ing. G. Pietrangeli Srl, Via Cicerone 28 – 00193 Rome

1. Introduction

Koysha, located in the Southern Nations, Nationalities and Peoples' Region of Ethiopia, is the fourth plant of the Gibe-Omo cascade comprising Gilgel Gibe (IP=200 MW), Gibe II (IP=420 MW) and Gibe III (1'870 MW) all in operation.
The plant, under construction, includes a 200 m high RCC gravity dam, a large gated spillway on the left bank capable to discharge up to 20'000 m^3/s and an open air powerhouse housing 6 Francis turbines fed by 2 steel penstocks crossing the dam body. Koysha, with its 1'800 MW of installed power and 6'340 GWh of annual energy production, is one of the most important projects in the Ethiopian Government's commitment to meet the country's present and future power requirements. The Ethiopian Electric Power company (EEP) is the employer, WeBuild SpA the EPC general contractor and Studio Pietrangeli Srl the designer.

The present paper deals with the geotechnical characterisation of the conglomerate formation which outcrops on the right abutment of the dam site, overlying the lower Andesite formation (where most of the dam is founded). Conglomerate formation is composed by a variable proportion of cobble and gravel sized basalt and rhyolite-trachyte sub-rounded elements surrounded by a weak matrix of fine sand and silt particles. The geotechnical characterisation of such a complex and heterogeneous medium (often defined in literature as "Block-In-Matrix rock" [1], [2], [3]), is fundamental for dam foundation and slope stability assessment. However, the evaluation of its strength and deformability properties resulted in a very challenging task due to the substantial impracticality in collecting high quality, undisturbed and representative samples [4] and [5].

The mechanical behaviour of the conglomerate has been therefore assessed mainly by means of a series of in-situ large scale shear tests and plate load tests carried out within a purposely excavated 70 m long inspection tunnel.
A large shear apparatus was conceived for testing nearly undisturbed blocks up to 0.8 x 0.8 x 0.4 m. The large-scale shear apparatus was formed by a shear box made of reinforced concrete, a vertical jack exerting the normal force and a sub-horizontal jack applying the shear force. During testing, normal, shear and lateral displacements were measured as well as force variation. After each test, the granulometric distribution, Atterberg limits of the matrix and the roughness profiles of the failure surface were determined for each block. In addition, to investigate the strength of the conglomerate/RCC contact, the same large-scale shear apparatus was used to test blocks of RCC casted above the conglomerate.

2. Geological settings

The site area consists almost entirely of volcanic rocks composed by Andesitic and Basalt Andesitic flows (A-Formation) that form the lower part of the stratigraphic sequence. This unit belongs to a pre-rift phase and is constituted by a continuous layered sequence of sub-aerial lava flows some meters thick, dipping towards West at low angle. According to its textural characteristics the A-Formation is divided into a brecciated (B1) and massive member (B2). Both members formed mainly during the quenching of the lava flows. No unconformities in the stratigraphic succession were observed except for decomposed to highly weathered horizons formed after some break during the lava emplacement.

The A-Formation is capped by the Conglomerate Formation (C) on the right bank and by the Columnar basalt Formation (Bc), which constitutes the top of the plateau on both the banks (Figure 1).
The shape of the Conglomerate Formation is that of a flat top surface dipping 4-17° toward 216-222 N, with a morphologic low located 600 m downstream of the dam axis.

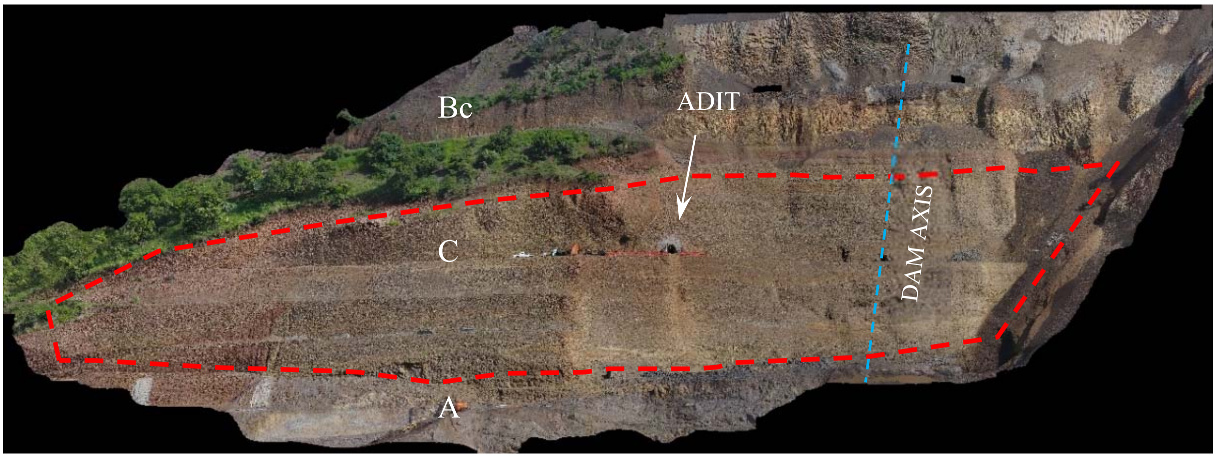

Fig. 1. Geology of the right dam abutment.

The Conglomerate formation is composed by two members:

- CONGLOMERATE (Co) (92 % of C-Formation) – The Conglomerate member (Co) covers almost the totality of the C-Formation. It is composed by unweathered to moderately weathered gravel and pebble clast supported conglomerate mainly formed by basalt and rhyolite-trachyte rounded elements. In the drilled cores, it occurs as a cemented, strong to moderately strong rock. The matrix is predominantly composed by sand and silt in varying proportions.
- SILTSTONE AND SANDSTONE (Cs) (8 % of C-Formation) – These two rock types appear as a brown and moderately strong rock. Rock cores have generally a low RQD value. Cs levels are placed at the top of the conglomerate formation or as intercalations.

The C unit formed in a fluvial sedimentary environment related to alluvial fans and\or braided river. The typical sedimentary succession is illustrated in Figure 2. The Cs lenses outline the following main characteristics:

- A lateral downlap geometry in the foreset portion of the fluvial bar.
- A paleocurrent indicating a roughly right to left direction truncated by subsequent channel in a higher fluvial energy period.
- An average thickness generally less than 50 cm (locally up to 1 m).

Fig. 2. Depositional geometries in the C unit with sandy bars and subsequent cutting channels.

The granulometric curves of Conglomerate samples are reported in Figure 3 whereas some index properties derived from laboratory testing on remoulded samples are shown in Table 1. The Co formation can be classified according to the USCS classification as a Poorly Graded Gravel (GP) with a minor content of material passing through sieve

0.075 mm (5% on average), generally with low plasticity. Samples taken from the inspection gallery where the in-situ shear tests have been carried out have an average saturation degree (Sr) of 90% and a void index (e) of 0.23.

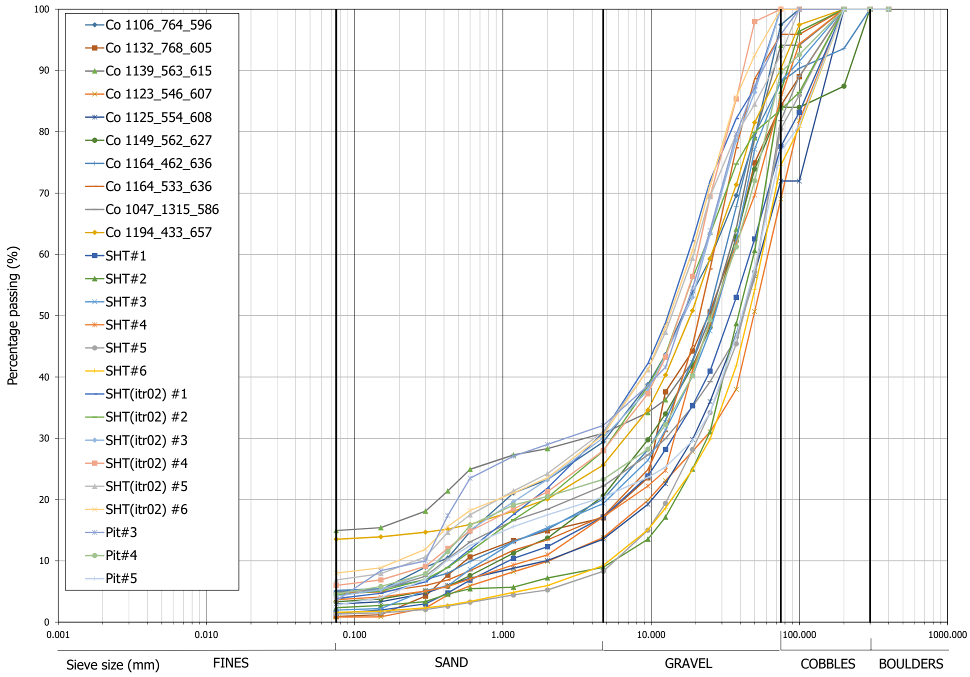

Fig. 3. Granulometric curves of Conglomerate samples from sieve analysis.

Tab. 1. Geotechnical index properties of the conglomerate and the matrix.

Conglomerate			Matrix		
γ (kN/m^3)	Sr (%)	e (-)	γ (kN/m^3)	w_L	I_p
25	90	0.23	20	45	13

3. In-situ large scale shear tests

3.1. Testing procedure

Due to the practical difficulty in collecting undisturbed samples for laboratory testing, 8 in-situ large scale shear tests have been performed to determine the strength parameters of the Conglomerate according to the procedure presented by [6], [7] and [8]. The tests were carried out inside a 70 m long inspection gallery excavated in the Conglomerate Formation below the ground water level as to ensure near-fully saturated conditions of the material. The testing apparatus is reported in Figure 4.

The following testing procedure has been adopted:

- PREPARATION: each block is carefully cut to the required dimensions (800 × 800 × 400 mm) avoiding disturbance and loosening of the material. The block is then encapsulated into a reinforced concrete pad isolated from the ground by means of a polystyrene panel.
- CONSOLIDATION: the normal load is gradually increased up to the full value determined for the test by means of a vertical hydraulic jack and a steel section helping to distribute uniformly the load to the test block. In this phase, the pore water pressure in the block dissipates under full normal stress before the shear load is applied. The consequent normal displacement is recorded. The consolidation phase is considered completed when the rate of change of normal displacement recorded at each gauge is less than 0.05 mm in 10 minutes. In all tests, the applied normal stress ranges in the interval sn = 0.3 ÷ 1.0 MPa, selected according to the expected stresses induced by dam load.
- SHEARING: the shear force is applied continuously at a rate of 0.1÷0.2 mm/min using a second hydraulic jack inclined at an angle of 20° with the horizontal to have the resultant line of applied shear force passing through the centre of the base of the shear plane. Shear force is measured by means of a digital load cell inserted between the hydraulic jack and the load distribution steel section. During testing the normal and

lateral displacements are continuously monitored by means of displacement gauges installed on three faces of the test block. Data are plotted as indicated in Figure 5.

- BLOCK INSPECTION: after the completion of each test, the blocks are turned upside down and cleaned. The profiles of the upper and lower shearing surfaces are surveyed with the Barton's profilometer and by means of photogrammetric techniques. The grading curve of each block and the index properties are determined in the laboratory.

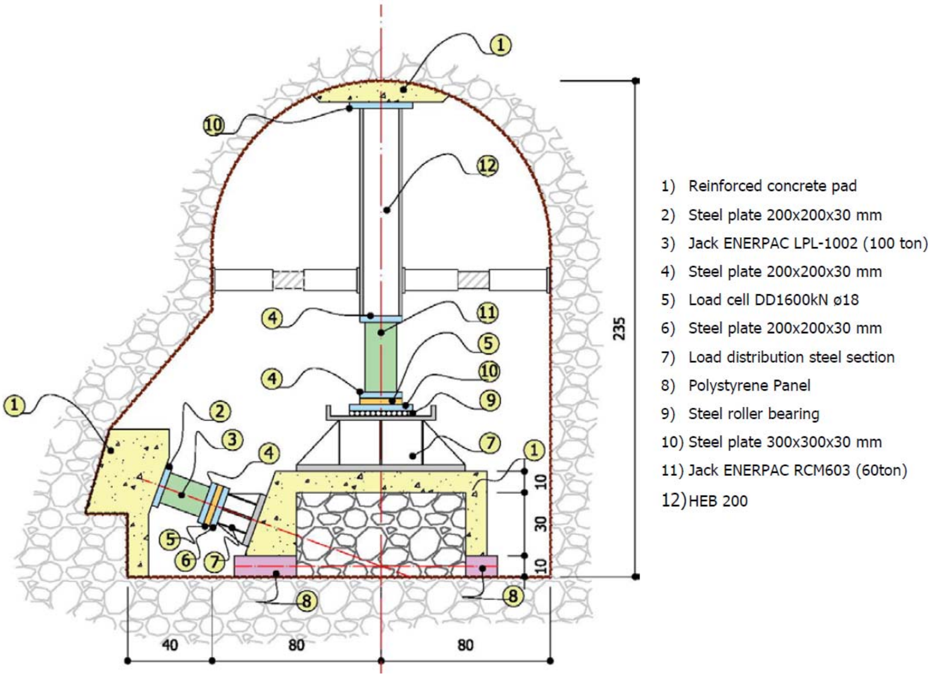

Fig. 4. Layout of in-situ large scale shear test apparatus.

A typical shear stress-shear displacement curve recorded during the in-situ shear tests is reported in Figure 5. The normal displacement measured during testing is also shown. The test blocks show a clear dilatant behaviour with well-identified peak and residual strength. The normal displacement decreases in the first phase of the tests and then increases following the change in volume of the test block.

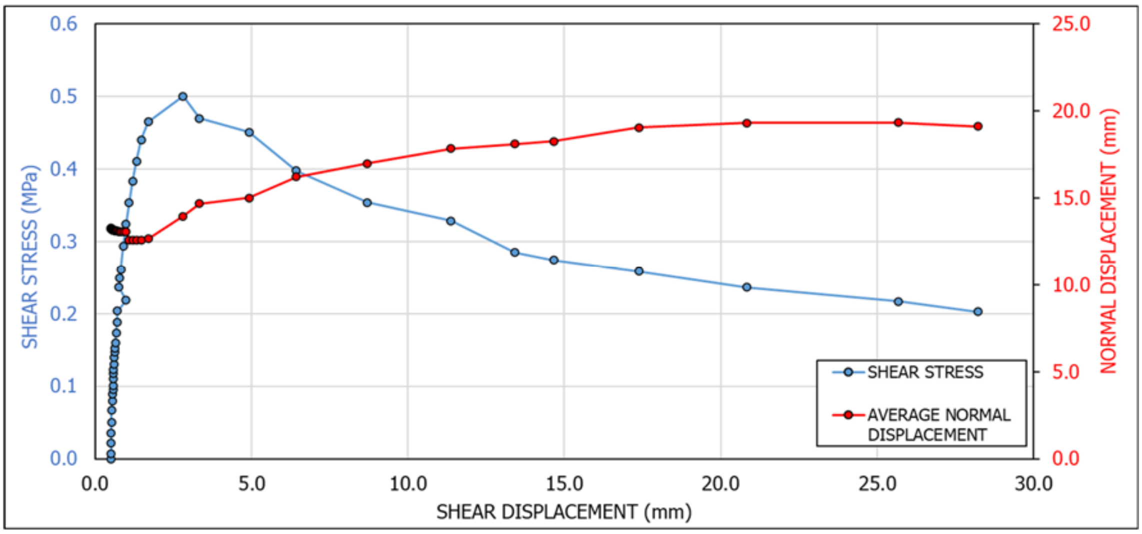

Fig. 5. In-situ large scale shear test, typical shear stress vs displacement curves (block 02B).

After the execution of the tests on Conglomerate, 6 GE-RCC (Grout enriched rolled compacted concrete) blocks have been poured and vibrated at the same location to investigate the shear strength of the contact GE-RCC/Rock. Two different RCC mixes have been tested with different content of cement (190 and 155 kg/m^3).

The GE-RCC/Rock shear tests have been carried out about 60 days after the casting of the GE-RCC blocks, applying the same procedure used for Conglomerate blocks.

3.2. Test results

Test results have been elaborated according to the procedure reported in [6] and [7]. Shear t and normal sn stresses are computed as follows:

$$\tau = \frac{P_s}{A} = \frac{P_{sa} \cdot cos\alpha}{A} \quad (1)$$

$$\sigma_n = \frac{P_n}{A} = \frac{P_{na} + P_{sa} \cdot sin\alpha}{A} \quad (2)$$

Where:

Ps	shear force
Pn	normal force
Psa	applied shear force
Pn	applied normal force
α	inclination of the applied shear force
A	area of the shear surface

The linear interpolation of the results of Conglomerate shear block tests (Figure 6) provides the peak and residual strength parameters reported in Table 2.

Table 2. Peak and residual shear strength parameters derived from in-situ shear testing.

	Peak	*Residual*
c (kPa)	140	0
ϕ (°)	42	35

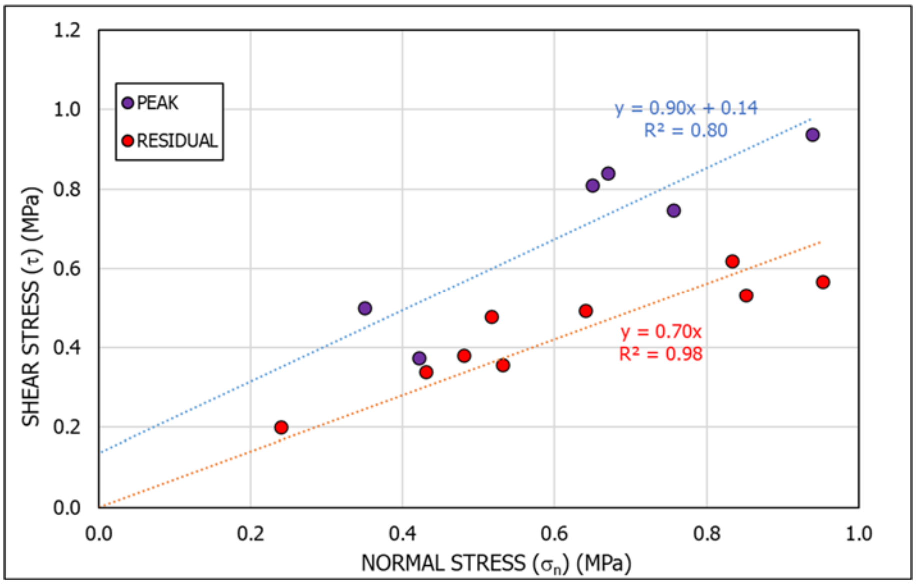

Fig. 6. Shear strength vs normal stress results with linear interpolation of the peak and residual values.

Test results of GE-RCC blocks are reported in Figure 7. Two different mixes have been tested:

- Blocks 01, 02 and 03
  - Aggregates — 50% Columnar Basalt + 50% Andesite
  - Grout — l/m³ — 100 — (W/C = 0.98)
  - Cement — kg/m³ — 190 = 115 + 75 — (Derba PPC 42.5)
- Blocks 04, 05 and 06
  - Aggregates — 50% Columnar Basalt + 50% Andesite
  - Grout — l/m³ — 90 — (W/C = 0.98)
  - Cement — kg/m³ — 155 = 85 + 70 — (Derba PPC 42.5)

Estimated cohesion ranges between 110 and 430 kPa, with the highest values observed for the mix with higher cement content. The friction angle appears less dependent on the cement content and varies between 42° and 43.5°, close to that of the Conglomerate blocks. Shear strength of GE-RCC / Conglomerate contact is higher than that measured for the Conglomerate blocks. As already mentioned, these values have been measured 60 days after GE-RCC casting. According to [9], an increase of the GE-RCC/Conglomerate contact shear-strength should be expected over time.

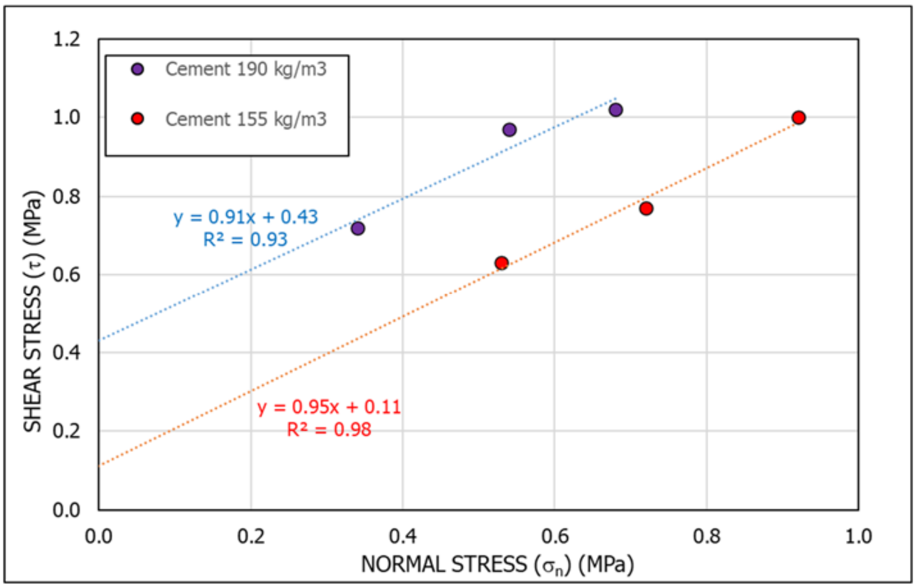

Fig. 7. GE-RCC, shear strength vs normal stress values @ 60 days with linear interpolation of test results

4. In-situ Plate Load Tests

No. 6 plate load tests were performed inside the inspection tunnel in the same position used for large scale shear tests. Each test consists of 5 cycles of load up to 30, 60, 90, 120 and 150 kN subdivided into No. 10 steps of ascending and descending load. Maximum and minimum load have been maintained for 10 minutes. Displacement of Conglomerate surface were measured by means of two series of micrometres arranged at 120° and at a distance equal to 1.2 and 1.5 times the radius of the plate, as shown in Figure 8.

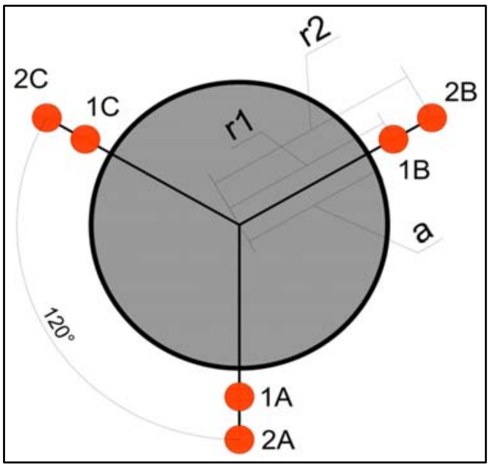

Fig. 8. Plate Load Test arrangement

Assuming that the rock-mass behaves as an elastic, homogeneous and isotropic mean, the displacement w in the direction of the load can be expressed by means of the following equation:

$$w = kap\frac{1-\upsilon^2}{E} \qquad (3)$$

Where:

a	plate radius
p	average pressure on plate
ν	Poisson coefficient
k	coefficient variable with the position of the measuring point with respect to the centre of the plate and the relative stiffness of the plate with respect to the rock mass (Figure 9)

It should be noted that at the distance of the reading points from the plate centre used in the test (r_1=1.2a, r_2=1,5a), the influence of the plate stiffness is negligible.

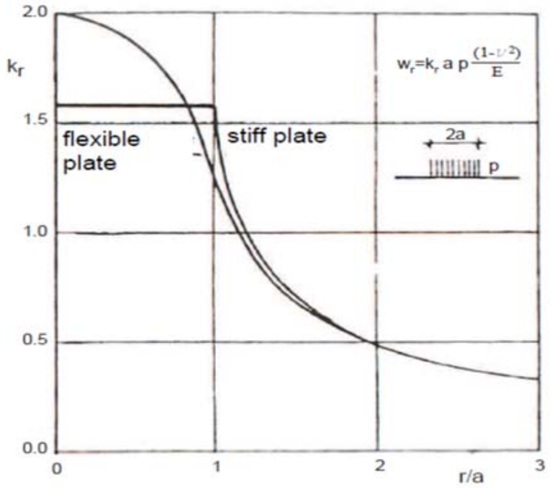

Fig. 9. surface displacement varying as a function of K

Frequency distribution of the elastic moduli, calculated in correspondence of each sensor for all the blocks and loading cycles, both for loading and unloading phase is reported in Figure 10.

The following observations are reported:

- Frequency distribution of calculated moduli shows the presence of some high values which may be related to the local inhomogeneity of conglomerate. These high values have been observed mainly in the sensors closer to the plate, both in loading and unloading phases.
- About 70% of the calculated values of the whole data set is between 400…1’300 MPa which corresponds to about half of the value obtained by means of Goodman Jack tests carried out in vertical boreholes.
- In correspondence of higher loads, the values of moduli are slightly more scattered and the average values are slightly lower.

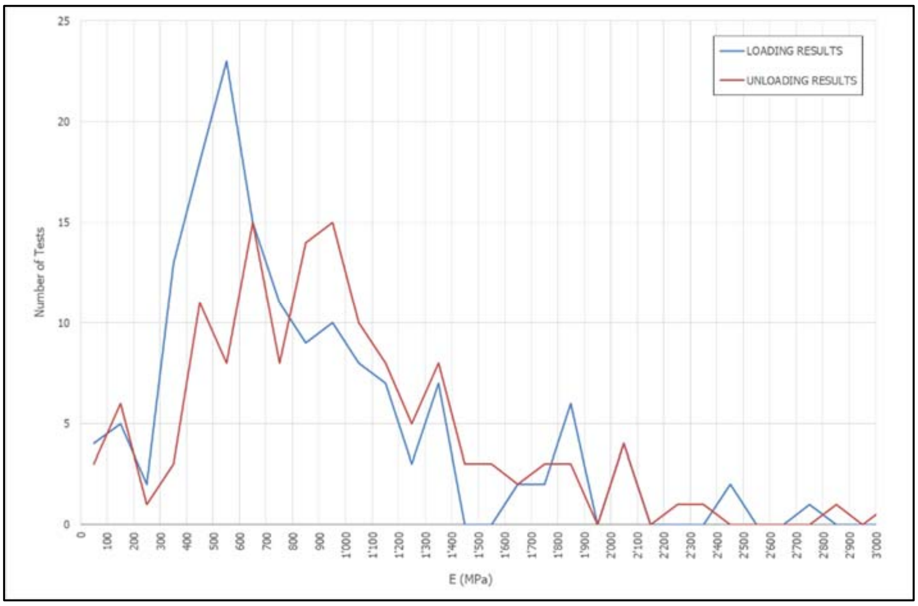

Fig. 10. frequency distribution of calculated moduli

5. Conclusions

The determination of the mechanical parameters of Conglomerate (strength and deformability) to be used for the design and stability analyses of the portion of Koysha dam founded on this formation resulted in a very challenging task, due to the heterogeneous nature of Conglomerate and the practical impossibility of collecting undisturbed samples. From a geotechnical point of view, the Conglomerate can be defined as a bimrock composed of hard blocks in a weaker matrix. In-situ direct shear tests performed by means of a full-scale testing apparatus capable

of testing Conglomerate blocks of dimensions 800 × 800 × 400 mm have been carried out to determine its strength parameters. Interpretation of the test results identifies a peak friction angle and a cohesion of the conglomerate of 42° and 140 kPa, respectively. These values are in agreement with the prediction model proposed by [10] to estimate the overall strength of the bimrock for a Volumetric Block Proportion (VBP) ranging between 30% and 40%, corresponding to blocks larger than 40÷50 mm according to the sieve analyses [12]. Shear strength of GE-RCC / Conglomerate contact resulted higher than that measured for the Conglomerate blocks having higher cohesion (110…430 kPa, increasing with cement content) and similar friction angle (42…43.5°).
Plate Load tests, excluding spot high values which may be related to the local inhomogeneity of conglomerate, provided a modulus in the range of 400…1'300 MPa. These values have the same order of magnitude of the ones obtained by means of Goodman Jack tests carried out in vertical boreholes.

References

[1] Medley E 1994. The engineering charcaterization of melanges and similar block_in_matrix rocks (bimrocks). *Dept of Civil Engineering, University of California, Berkley, California, PhD diss*

[2] Medley E and Lindquist E S 1995. The engineering significance of the scale-independence of some Franciscan melanges in California, USA. *Proceeding of the 35th US Rock Mechanics Symposium, Reno, 907-914, Rotterdam Balkema*

[3] Medley E 2008. Engineering the Geological Chaos of Franciscan and Other Bimrocks. *Proceedings of ARMA 2008 - American Rock Mechanics Association, 42nd Rock Mechanics Symposium, San Francisco, June 28-July 5 2008.*

[4] Napoli M L, Barbero M, Scavia C 2019. Slope stability in heterogeneous rock masses with a block-in-matrix fabric. *14th International Congress on Rock Mechanics and Rock Engineering, ISRM 2019; Foz do Iguaçu; Brazil; 13-18 September 2019*

[5] Napoli M L, Barbero M, Scavia C 2021. Tunneling in heterogeneous rock masses with a block-in-matrix fabric. *International Journal of Rock Mechanics and Mining Sciences, Vol. 138, February 2021*

[6] ISRM 1974. Suggested Method for in situ determination of Direct Shear Strength. *The Complete ISRM Suggested Method for Rock Characterization, testing and Monitoring*

[7] ASTM D4554-02 2002. Standard Test Method for In Situ Determination of Direct Shear Strength of Rock Discontinuities. *ASTM International, West Conshohocken, PA*

[8] Coli N, Berry P, Boldini D, Bruno R 2009. In situ large size non-conventional shear tests for mechanical characterization of a BIMROCK in the Santa Barbara open pit mine (Italy). *43rd US Rock Mechanics Symposium – Ashville*

[9] Nawy G E 2008. Concrete Construction Handbook, *Taylor and Francis*

[10] Kalender A, Sonmez H, Medley E, Tunusluoglu C, Kasapoglu K E 2014. An approach to predicting the overall strengths of unwelded bimrocks and bimsoils. *Eng. Geology 183, 65-79*

[11] Tsiambaos G 2010. Engineering Geological Behaviour of Heterogeneous and Chaotic Rock Masses. *Bullettin of the Geological Society of Greece, Vol. 43.*

[12] Pittalis G 2021. In-situ shear strength testing oof conglomerate formation for a large RCC dam. *Mechanics and Rock Engineering from Theory to Practice - the 2021 ISRM International Symposium Eurock 2021, Turin*

The Authors:

G. Pittalis, obtained his degree in Civil and Environmental Engineering from the University of Rome "La Sapienza". He works for Studio Pietrangeli as senior dam & hydropower engineer gaining important experience in the feasibility, design and construction of dams, hydropower plants and large hydraulic works in many African countries and South America. His expertise ranges from hydraulics to rock-mechanics and geotechnics, instrumentation and dam monitoring.

A. Delisio, obtained a PhD in geo-mechanics at the Ecole Polytechnique Fédérale de Lausanne and a degree in Civil and Environmental Engineering at Politecnico di Torino. He has a broad experience in geotechnical engineering for infrastructures, underground excavations, gained in large construction projects in Switzerland and Europe. He joined Studio Pietrangeli in 2019 as a senior geotechnical engineer dealing with geotechnical design of dams, site characterization and monitoring.

C. Rossini graduated with honors in civil engineering from the University of Rome "La Sapienza". He specialized in rock mechanics and since working with Studio Pietrangeli has been deeply involved in the study and design of RCC mixes for the large dams of Gibe III and GERdp.

V. Millesi, while completing his degree in Civil Engineering at the University of Rome "*La Sapienza*", has been working for Studio Pietrangeli and has acquired substantial experience in the field and in-depth knowledge relating to the feasibility, design and construction of large-scale civil works such as dams and hydropower plants in Africa with particular regard to geo-mechanics, field activities and dam monitoring.