PROPOSAL OF CORRELATION AMONG DIFFERENT SOIL BEARING CAPACITY PARAMETERS BASED ON AN EXTENSIVE TEST CAMPAIGN

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Abstract: Soil characteristics play a key role for design and construction of transportation infrastructures. Subgrades of pavements must be adequately designed and realized to face stress-strain fields due to vehicles, withstanding traffic loading during construction and service life and limiting deformations to prevent the pavement failure. The evaluation of the soil bearing capacity can be performed through different laboratory and in situ tests, both static and dynamic. Among the existing methods, Light Falling Weight Deflectometer (LFWD), static plate-bearing load tests (PBLT), Dynamic Cone Penetrometer test (DCPT) and California Bearing Ratio (CBR) tests can be cited. LFWD can be quickly used, being it a simple and portable equipment suitable for determining the stiffness modulus of the soil. Static plate-bearing load tests can be carried out to measure the elastic vertical displacements, obtaining the so-called modulus of reaction or modulus of deformation as a function of the plate diameter and the stress path. DCP is used to measure the resistance against penetration of a soil through a simple test. Then, such characteristic is generally correlated to CBR using empirical correlations. As known, the bearing capacity of a soil is strictly related to its degree of compaction. Given this background, an attractive aspect from a scientific and technical perspective concerns the correlation among different methods and parameters to determine a general approach in considering the different data available for the design and control of a soil layer. To this regard, the present paper shows the results of an extensive in-situ survey and laboratory experimentation assessing the bearing capacity of soils through the above-mentioned techniques: a huge data-base permitted the development of some correlations between the different static and dynamic data.

Keywords: bearing capacity, soil, in situ survey, laboratory experimentation, dry density.

1. Introduction and Experimental Approach

The availability of possible correlations among different bearing capacity parameters is essential for a better approach to the road design and construction. Bearing capacity measurements are often performed with a single technique, mainly depending on the available in-field or laboratory equipment; for this reason, the correlation of data deriving from different tools or methods is required, even if not always simple, given the complexity and the huge amount of physical variables involved in the measurement. Bearing capacity of soils (and, generally, unbound/bound granular materials for transport infrastructures) can be determined though several methods, using different instruments able to acquire different parameters. Principally, tests can be divided in static or dynamic ones. Static analysis generally considers the use of circular plates, loaded with heavy contrast weights (some standards require loads greater than 5 tons) and quite long loading procedures. Differently, dynamic tests usually imply advanced equipment that allows easy and timesaving surveys and tests. Both approaches can be used in field or laboratory tests. Among the existing in-situ tests, Light Falling Weight Deflectometer (LFWD) or Portable Falling Weight Deflectometer (PFWD), static plate-bearing tests and Dynamic Cone Penetrometer test (DCPT) can be cited. In laboratory, the California Bearing Ratio (CBR) test represents one of the most important solutions for the evaluation of materials' strength. The parameter suitable for the characterization of the bearing capacity varies according to the test: the dynamic modulus E_{vd} (MPa) is calculated with the LFWD, the California Bearing Ratio index (CBR, in percentage) can be estimated in field with the DCP tool or evaluated in laboratory with the CBR test, the reaction modulus k (MPa/m) and the deformation modulus M_d (also named static modulus, in MPa) are determined by means of a static bearing load plate test (the different parameter - k or M_d – depends on the size of the plate, loading steps and level). Several researchers analyzed benefits and drawbacks of such testing procedures and dealt with possible correlations of the parameters, validating experimental data and results (Ese et al., 1994; Loizos et al., 2003; Adam et al., 2009; Fleming et al., 2009). Frequently, studies found adequate relations analyzing the influence of variables which affect bearing capacity, based on soil grading, Atterberg limits, in-field specific weight, optimal Proctor density, natural moisture or optimum (Proctor) humidity content (Lim et al., 2014; Patel et al., 2013; Talukar, 2014; Sangiorgi et al., 2006). Correlations between static and dynamic parameters are substantially known. In 1995, the Institute for Transport Sciences of Karlsruhe (Gemany) elaborated a relation between dynamic modulus E_{vd} and static modulus M_d ("*Baksay formulation*") with the following equation: $E_{vd} = (0.52 \cdot M_d)+9.1$ (MPa). Tompai (2008) proposed efficient formulas to relate dynamic modulus of soils measured with the Light Falling Weight Deflectometer (LFWD) or similar instruments with the modulus derived from a static load plate, also comparing the findings with alternative correlations available in literature. Links between CBR index and static modulus were identified with empirical approaches by Rafiroiu (1971) and Jeuffroy (1967). Based on the analysis of various data from literature, Rafiroiu proposed two relations for the static elastic modulus E_{st} considering the average statistic distribution: $E_{st} = 3 \cdot CBR$ [MPa] for cohesive soils; $E_{st} = 5 \cdot CBR$ [MPa] for non-cohesive ones. CBR index of a compacted sample was measured in laboratory using the same density obtained in-field during static plate tests. Formulas were then validated trough an experimental survey with the determination of the static modulus of elasticity at the second loading cycle with a 30 cm diameter plate. Independently from the soil nature, Jeuffroy proposed the correlation $E_{st} = 6.4 \cdot (CBR)^{0.65}$, in MPa, even if a poor scientific background caused a weak reliability. Alternatively,

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Sargious found a correlation between the CBR index and the reaction modulus k; it was a bilateral-shaped curve, where the first part, for CBR values ranging from 2 to 30, was represented by the equation $k = 4.1+51.3\cdot\log(CBR)$ [MPa/m], and the second one, for CBR from 30 to 100, was governed by $k = -314.7+266.7\cdot\log(CBR)$ [MPa/m]. Depending on the soil type, Sangiorgi et al. (2006) proposed a relation between deformation modulus M_d and dynamic modulus E_{vd}, effective for M_d values higher than 50 MPa: $E_{vd} = (0,2\cdot M_d)+(18,2\pm 2,4)$. Also Kim et al. (2007) performed a lot of tests in order to identify a possible correlation between M_d and E_{vd}: in addition, they certified the significant cost save related to the substitution of the static plate tests with dynamic LFWD ones. Harison (1987) developed theoretical explanation for the linear log-log relation between DCP and CBR, conducting tests on clay-like, well-graded sand, and well-graded gravel samples prepared with standard CBR molds: moisture content and dry density parameters resulted key aspects for the CBR-DCP correlation. Truebe et al. (1995) evaluated the strength of a low volume road managed by the Forest Service in USA by means of the DCP, presenting a correlation between this apparatus and in-field CBR for unbound layers and subgrade. They furtherly reported the efficacy of DCP in the quick evaluation of strength properties. Interesting DCP-CBR relations were also published by Abdulrahman (2015). Wyroslak (2017) found other equations among the above described bearing parameters, depending on the state of surface layers of soil. Varghese at al. (2009) studied relations between LFWD, DCP and CBR parameters in order to define easy tools for the conversion of such physical quantities.
Given this introduction, the herein study presents the results of several in-situ and laboratory tests aimed at identifying some correlations between the main bearing strength parameters. Tests, described in more detail in the following paragraph, were executed within a vast unbuilt area of the Northern Italy, close to a major infrastructure. Inside this area, rectangular shaped, a reference central axis was identified: 3 alignments, parallel to the axis, were defined at a distance of 53, 75 and 105 meters on both sides (the northern and southern side are hereafter named “a” and “b” respectively). Perpendicularly to the reference alignment, 10 sections on the “a” side and 12 sections on the “b” side were drawn (at a distance of 200 meters one from the other) in order to define the location of the bearing tests. In some cases, the test sites were shifted some meters when ducts and pipes were detected close to the position. In the same area, some soil samples were taken to be analyzed in the laboratory. Figure 1 shows the layout of the test site (reference axis, “a” and “b” alignments, test and sampling sections). Since investigation required about two weeks of work, soil water content calculated with specific procedures was supposed to vary during the experimental campaign.

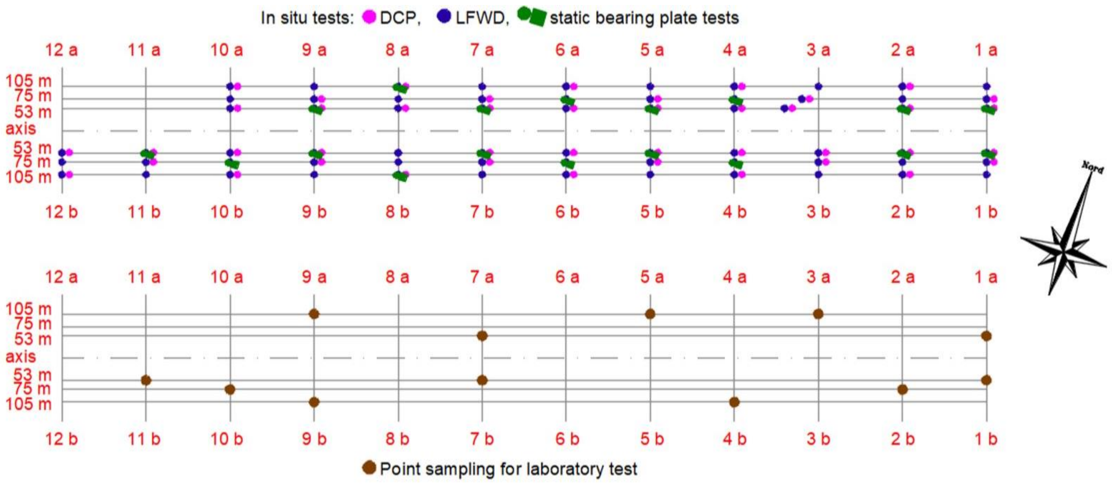

Fig. 1.
Tests and sampling area

2. Methods and Experimental Data

Data used for the present work were collected during in-situ and laboratory tests. In-field tests consisted in static and dynamic measurement of bearing capacity of soils: the more complex and time-consuming tests (depending on the equipment set up and the need of contrast truck machines) were carried only in some indicative sections (Figure 1); on the contrary, easier and faster tests (e.g. LFWD) were executed in all the sections. The following tests were carried out: Light Falling Weight Deflectometer (LFWD) tests, static plate-bearing tests, Dynamic Cone Penetrometer tests (DPCT) and sand cone tests. Light Falling Weight Deflectometer (ASTM E2835-11) allows the dynamic testing of soils and involves a quick procedure; for this reason, it was used in all the sections: the output parameter of LFWD is the dynamic modulus E_{vd}. Static plate-bearing load tests (according to Italian standards, CNR 146/1992 and CNR 92/1983) were carried out only in some points, determining the deformation modulus M_d (300 mm diameter steel plate) and the reaction modulus k (760 mm diameter plate). DCP tests, performed in two replicates for all sections, allowed the estimation of the CBR index throughout a relation given by the US Army Corps of Engineering (ASTM D6951). Finally, sand cone test was used to determine the in-field specific weight of the soil (Italian standard, CNR 22/1972): tests were carried out only in some representative zones. Then, in the laboratory, collected samples were subject to grading analysis (EN 933-1 and EN 933-2) and Atterberg limit’s determination (CEN ISO/TS 17892-12); soils were classified according to the Unified Soil Classification System (USCS). Furthermore, Proctor specimens were compacted according with standards (EN 13286-2), adding the specific quantity of water corresponding to the pre-determined natural humidity. Part of the samples were tested suddenly after the compaction to calculate the immediate bearing index (IBI) (EN 13286-47); the other ones were subject to soaking 4 days (EN 13286-47) in order to evaluate swelling and CBR index after immersion.

Freeze-thawing tests were performed using an original protocol to evaluate the soil frost resistance: samples, after Proctor compaction, were sealed with plastic bags (to maintain humidity) and subject to freeze-thawing cycles. The samples were subject alternatively to freezing at -15°C, 50% humidity, for 12 hours and thawing at 20° C, 50% humidity, for 12 hours. The freeze-thawing cycle was repeated 6 days. After the 6th day, the samples were moved in a room at 20°C for 24 hours and then the compressive strength was measured.

Grading, Atterberg limits and water content are reported in Table 1. According to the USCS, the soil can be classified as "*silty sand, sand-silt mixture*" (acronym "*SM*"). Two samples coming from 1a and 9b sections were classified as "*poorly-graded gravel, gravel-sand mixture, little or no fine*" (acronym "*GP*") and "*inorganic silt and very fine sand, rock flour, silty of clayey fine sand or clayey silt with slight plasticity*" (acronym "*ML*"), respectively. Considering the classification prescribed by the Italian standard UNI 11531-1:2014 (based on the AASHTO classification), most of the specimens resulted as "*silty-sand soil*" ("*A2-4*" code). Table 1 resumes the results obtained for each test position. Table 2 and 3 summarize the in-field tests results, reporting the type of test and the corresponding parameter. Table 2, related to sand cone tests, shows natural soil moisture (%), bulk density (Mg/m^3) and dry bulk density (Mg/m^3). Table 3 shows plate-bearing load tests results (k, in MPa/m, and M_d, in MPa), LFWD moduli (E_{vd}, in MPa) and Dynamic Cone Penetrometer data (DCP in mm/blow and CBR in %). Table 4 summarizes the results obtained with laboratory tests: CBR index [%] after Proctor compaction, initial h_i and final h_f specimen height [mm] (before and after soaking, respectively), swelling Δh ($h_f - h_i$ difference), strength resistance before (R_C, in MPa) and after the freeze-thawing cycles ($R_{C\text{-}F/T}$, in MPa). The parameter (R_C - $R_{C\text{-}F/T}$)/R_C (in %) is used to evaluate the resistance variations after freeze-thawing cycles. In general, an overall consideration of results points out that studied soils have a discrete bearing capacity (for static plate and LFWD tests, bearing capacity was always measured 20 centimeters under the surface after the grassy topsoil removal).

Table 1

Grading analysis, Atterberg limits and classification results for in-field soil samples

	Sampling points												
	1a	**1b**	**2b**	**3a**	**4b**	**5a**	**7a**	**7b**	**9a**	**9b**	**10a**	**10b**	**11b**
Grading analysis													
Sieve size [mm]	**Passing [%]**												
2.00	94.0	99.0	93.0	99.9	97.0	82.0	96.5	94.0	99.0	99.9	100.0	97.0	90.1
0.4	46.0	82.0	72.0	92.9	85.0	71.0	88.8	81.0	89.0	97.5	92.0	87.0	81.1
0.063	4.0	27.0	16.0	40.4	30.0	15.0	27.9	7.0	25.0	56.0	41.0	23.0	33.4
Atterberg limits													
W_L [%]	22	17	23	18	18	17	19	19	19	19	17	21	20
W_P [%]	17	13	18	15	17	18	17	17	18	18	16	19	17
IP [%]	4	4	5	3	2	0	2	3	1	1	1	2	2
Classification													
USCS	GP	SM	SM	SM	SM	SM	SM	SM	SM	ML	SM	SM	SM
UNI	A1-b	A2-4	A2-4	A4	A2-4	A2-4	A2-4	A3	A2-4	A4	A4	A2-4	A2-4

Table 2

Sand cone test results: natural moisture and bulk density of soil

Sampling Points												
1a	**1b**	**2b**	**3a**	**4b**	**5a**	**7a**	**7b**	**9a**	**9b**	**10a**	**10b**	**11b**
Natural soil moisture [%]												
6.4	9.1	7.1	7.8	8.8	9.4	8.2	8.1	7.0	7.2	8.6	7.9	7.7
Soil bulk density with natural moisture content [Mg/m^3]												
1190	1540	1510	1310	1870	1510	1680	1660	1400	1480	1470	1720	1640
Soil dry bulk density [Mg/m^3]												
1050	1320	1310	1160	1620	1320	1450	1340	1230	1310	1320	1440	1380

Table 3

In field test results (from LFWD, static plate-bearing load tests, DCPT index and CBR by DCPT, respectively)

Sampling points	**E_{vd} [MPa]**	**M_d [MPa]**	**K [MPa/m]**	**DCP index [mm/blow]**	**CBR (from DCP) [%]**
1a	10.98	12.00	3.26	36.6	5
1b	15.23	21.33	---	12.9	22

Sampling points	E_{vd} [MPa]	M_d [MPa]	K [MPa/m]	DCP index [mm/blow]	CBR (from DCP) [%]
2a	15.12	14.56	1.64	21.2	16
2b	14.12	7.70	7.38	24.9	13
3a	9.93	---	---	22.7	9
3b	15.73	---	---	32.2	7
4a	8.98	16.25	9.43	29.6	7
4b	16.55	15.82	7.09	23.6	9
5a	11.68	36.63	8.79	18.7	12
5b	14.40	20.00	2.87	19.1	12
6a	11.20	27.69	7.21	23.1	12
6b	14.62	19.40	4.68	29.7	8
7a	12.15	22.56	4.66	24.4	9
7b	10.88	10.43	5.61	21.4	13
8a	17.77	16.76	15.67	26.6	8
8b	23.60	30.00	9.38	21.8	14
9a	21.62	10.32	7.75	27.0	18
9b	15.23	13.66	8.68	23.8	10
10a	14.67	---	---	18.4	19
10b	12.75	13.85	8.17	31.4	7
11b	13.98	20.13	6.62	18.6	12
12b	17.75	---	---	12.9	18

Table 4
Laboratory test results (IBI, CBR, expansion, frost resistance after freeze-thawing cycles)

Sampling points	IBI [%]	CBR [%]	h_i [mm]	h_i [mm]	Δh (=h_f - h_i) [mm]	R_C [MPa]	$R_{C\text{-}F/T}$ [MPa]	(R_C – $R_{C\text{-}F/T}$)/R_C [%]
1a	46	4	126.57	133.29	6.72	0.48	0.36	26
1b	15	27	124.51	127.25	2.74	0.38	0.29	24
2b	68	14	126.66	131.94	5.28	0.65	0.62	5
3a	51	38	124.99	126.77	1.78	0.73	0.64	12
4b	49	23	124.56	126.3	1.74	0.41	0.32	21
5a	58	32	124.38	126.62	2.24	0.45	0.27	41
7a	46	18	124.48	129.34	4.86	0.32	0.19	41
7b	34	24	124.58	128.17	3.59	0.27	0.27	1
9a	32	10	125.06	127.94	2.88	0.40	0.30	26
9b	61	8	124.18	130.61	6.43	0.52	0.49	6
10a	16	15	124.45	130.07	5.62	0.65	0.59	9
10b	48	31	152.62	128.49	2.87	0.46	0.29	36
11b	76	40	124.25	126.61	2.36	0.60	0.36	40

Values reported on Table 3 and 4 show a not good bearing capacity of the examined soils. Italian specifications for the construction of transport infrastructures introduce a classification based on parameter values. Soil investigated in this paper have: “middle” characteristics (CBR > 9% e k > 60 kPa/mm) if used as subgrade for road construction, “good” characteristics (15 % ≤ CBR ≤ 20 %) if used in airport safety strip or flexible pavement subgrade and “bad” characteristics if used as subgrade for railways or rigid pavement subgrade for airport infrastructures.
CBR indexes deduced from DCP tests and measured in the laboratory (after Proctor compaction and 4-days soaking) are sensibly different. Although literature reported that laboratory and in-situ (DCP) CBR values generally match (Sangiorgi et al., 2006), in this case a higher densification in the laboratory was observed and determined high CBR values if compared with those of in-situ samples; this was probably due to a low presence of fines and compactability characteristics. Table 4 also shows swelling results (height variation of samples confined in molds) after 4 days of soaking and the compressive strength (R_C) before and after freeze-thawing cycles ($R_{C\text{-}F/T}$). In general, soils seem to be

partially affected by freeze-thaw effects, with an expansion equal to approximately 5% and a compressive resistance decrease of 22%.

3. Developed Correlations

Considering the existence of several equations suitable for correlating different bearing capacity parameters, some of them were used to verify the possible correlation of results for the soils analyzed in the present work.
First of all, relating dynamic modulus E_{vd} (recorded with LFWD) and static modulus M_d (calculated with static plate-bearing load test), an acceptable correspondence seemed to exist (R^2 = 0,7). A plot is presented in Figure 2.
Using the Baksay, New Baksay, Rafiroiu_1 and Rafiroiu_2 equations (Figure 3), reliability of different formulations for E_{vd} versus M_d was verified. Baksay, "New Baksay" and Rafiroiu_1 formulas exhibited better confident relations (R^2 = 0,58) with respect to Rafiroiu_2 one, for which R^2 is equal to 0,43 (the lack of a stronger link can be probably ascribed to the low content of the fine fraction in soils). The equations used are the following: $E_{vd} = (0{,}52 \cdot M_d)+9{,}1$ for Baksay; $E_{vd} = 0{,}62 \cdot M_d$ for "New Baksay"; $E_{vd} = 1{,}1 \cdot M_d$ for Rafiroiu_1; $E_{vd} = (1{,}1+0{,}028 \cdot \alpha) \cdot M_d$ for Rafiroiu_2 (α is the percentage passing to 0,063 mm sieve). Using these equations to evaluate the real data, Figure 3 shows that "New Baksay" formula leads to an overestimation and Baksay formula to an underestimation of E_{vd}. Rafiriou_1 and Rafiroiu_2 formulas show an overestimation using low M_d values, and viceversa for high M_d values.

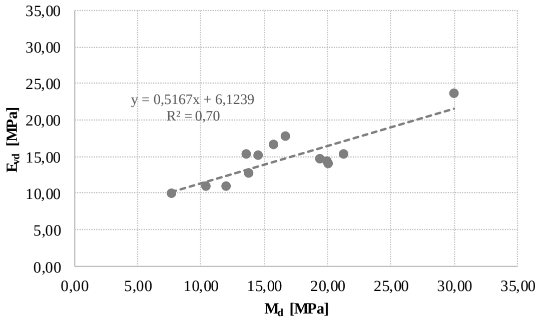

Fig. 2.
Relation between dynamic modulus Evd and static modulus Md

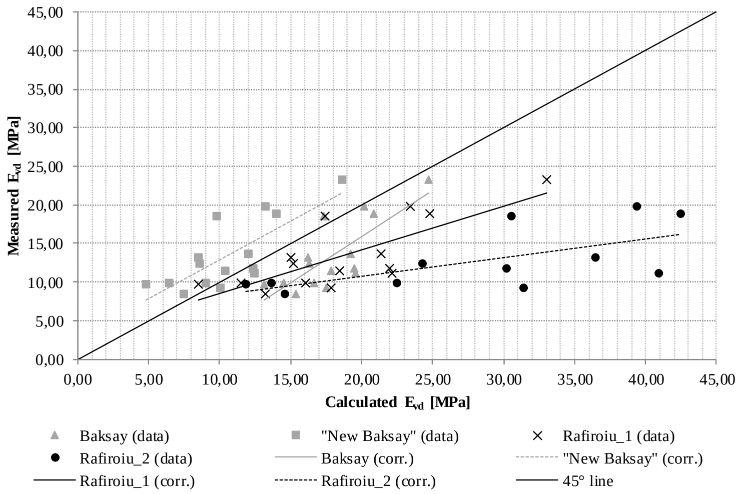

Fig. 3.
Relations between Evd (measured in situ) in the y-axis and different calculated Evd values in the x-axis

The relation between in-situ (DCP) and laboratory CBR index was also investigated. Figure 4 presents two relations: the first one (grey broken line) is the ASTM standard equation (between DCP in mm/blow and the CBR index in percentage) used to calculate the bearing capacity from DCP test; the second one (black dotted line) is the equation based on data from the field test (DCP) and laboratory test (CBR index). The Figure 4 shows that ASTM standard equation ($CBR = 292 \cdot DCP^{-1{,}12}$) underestimates the CBR values calculated in laboratory. The weak correlation between DCP and CBR index (measured CBR values are higher than those deriving from the ASTM standard equation) is caused probably by the better densification given by Proctor compaction in laboratory.

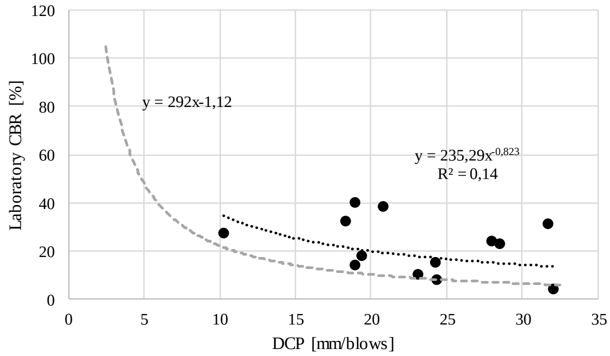

Fig. 4.
Relationship between laboratory CBR index and Dynamic Cone Penetrometer test (DCPT)

The correlations between static modulus E_{st} (in MPa) or deformation modulus M_d (in MPa) and laboratory CBR index (estimated from E_{st} or M_d) are presented in Figure 5. Jeuffroy formula ($E_{st} = 6{,}4 \cdot CBR^{0{,}65}$), Boussinesq equation ($E_{st} = 0{,}92 \cdot CBR$, with Poisson's coefficient equal to 0,4) and the equation $M_d = CBR/0{,}2$ (where deformation modulus M_d is measured in MPa – Ferrari et al., 1983) were used to estimate CBR indexes. Figure 5 represents: Jeuffroy formula, Boussinesq equation, the equation $M_d = CBR/0{,}2$ and the data distribution measured with in-field tests. Despite the quite low R^2 values, static modulus M_d is predicted with laboratory CBR indexes; Jeuffroy and $M_d = CBR/0{,}2$ formulas lead in this case to an underestimation of CBR values, but data show a fair fit with Boussinesq equation.

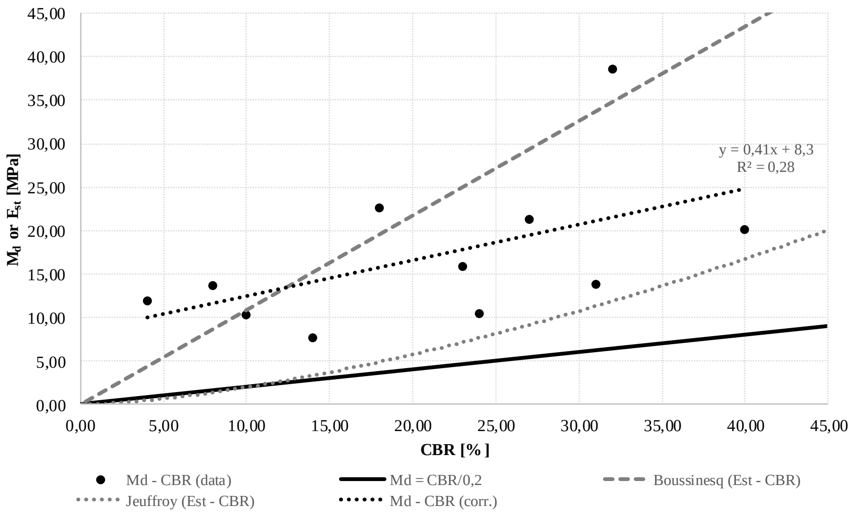

Fig. 5.
Relationship between CBR index and static modulus E_{st} or M_d

Figure 6 shows the correlation between static modulus (M_d) and reaction modulus (k); plotted data seemed to show no evident correlation between these two bearing capacity parameters.

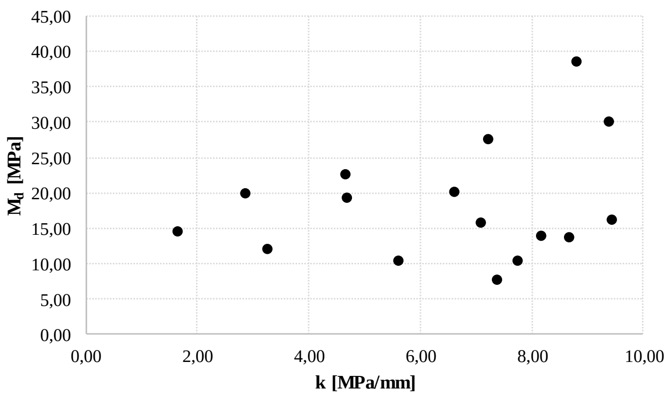

Fig. 6.
Relationship between measured static modulus M_d and measured reaction modulus k

4. Conclusions

An experimental study has been carried out on soils in order to determine the main mechanical parameters suitable for representing their bearing capacity. In field and laboratory tests have been performed involving the evaluation of static and dynamic moduli as well as current laboratory indexes in different operating conditions, with the purpose of defining possible correlations among the more common strength parameters. The first conclusion of the research was that tests carried out in laboratory, even if according to the standards in force, overestimate mechanical performances due to the different compaction conditions which guarantee a higher density of specimens: Proctor compaction procedures, CBR and IBI from laboratory tests lead to a less conservative classification of materials than in field trials. Generally, some correlation among the different parameters can be found, even if it is strictly related to materials' properties and test procedures. The dynamic modulus from LFWD is the most difficult parameter to be linked to other indexes due to the specific size of the tool, the loadings involved and the test protocol.
In any case, comparing the equations from in-field tests and literature, significant differences in form and coefficients were highlighted; soil characteristics (e.g. particle size distribution, etc.) play a crucial role. For these reason, more research is recommended in order to investigate better all the aspects which affect the typical parameters used to indicate the bearing capacity of soils.

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