Practice of the Doorstopper stress measurement method during the last 30 years in Italy

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Abstract. In Italy, during the last decades, most of the in situ stress measurements were carried a shallow depth, in existing geotechnical structures. In these cases, the stress measurements involves concrete or low disturbed rocks material; thus linear, elastic, non-fractured materials. For this reason the stress tests interpretation is straightforward and reliable. In these situations, since the early 90s, the Doorstopper technique became the most used stress measurement technique. It has proven to be effective and cheap. A collection of punctual tests can be interpreted with a suitable numerical model. The numerical model provide the interpolation of the punctual measurements and can give important information about the virgin stress field. After recalling the main features and improvements of the doorstopper method in the last 30 years, this paper illustrates two Italian cases. The first case is the Sparvo Tunnel (Bologna-Firenze highway) where was performed a massive measurement campaign made up of more than six hundred Doorstopper tests in two adjacent tunnels; the results of the two tunnel are compared; the 2d FEM model interpretation is discussed. The second case is a marble quarry in Alta Carnia (Udine): the Doorstopper and stress variation measurements were carried out and interpreted by means of a 2d FEM model, resulting in the definition of the natural stress field.

1. Introduction

Achieving a satisfactory knowledge of the in-situ virgin stress field may be still today a troublesome and expensive goal. This is particularly noticeable in complex rock formations as pelitic flyshees and highly tectonized clay-stones, where rock stress measurements are often unreliable, even no-feasible.

Also in “easier” rocks, the natural stress field is non-uniform in the domain of the underground excavation. For example: along a tunnel axis the natural stress varies due to overburden and lithological changes; in a cortical marble quarry chamber, the natural stress field varies with the distance from the slope.

In cases like these, a satisfactory knowledge of the virgin stress field can be impossible for economical and timing reasons, because it would require many punctual stress measurements.

Probably for these reasons, in Italy, during the last decades, most of the in situ stress measurements were carried a shallow depth, in existing geotechnical structures, typically: tunnel linings, retaining walls, rock walls of mechanical excavations. In French, in the last decade, many shallow stress measurements were carried out in the body of concrete dams. In Italy, more recently, shallow stress tests were carried out also in bridge pre-compressed concrete beams.

In all these situations, since the early 90s, the Doorstopper technique became the most used overcoring technique in the Italian practice. It has proven to be effective and cheap. Due to its small
size, it allows measuring the stress variation within the lining thickness. It is very efficient: in one working shift, up to 10 doorstopper tests can be performed by a 2 people team, each of test giving an independent stress measurement.

When the measurement involves linear, elastic, isotropic, non-fractured materials, as concrete or mechanically excavated low disturbed rock material, the stress tests interpretation is straightforward and reliable.

When the Doorstopper test is at shallow depth, the stress component parallel to the borehole is negligible. Thus, each single Doorstopper test can give and independent measurement of the plane stress normal to the borehole axis.

A collection of punctual tests can be interpreted with a suitable numerical model: for example, the 2d or 3d model of a lining ring in the case of a tunnel, or the 3d model of the underground chambers of a marble quarry. The numerical models give the interpolation of the punctual stress measurements and can provide important information about the virgin stress field, as the maximum stress direction and its magnitude.

2. The Doorstopper stress measurement technique

The Doorstopper technique is one of the earliest stress relief method developed for in situ rock stress measurements [1]. It was introduced in Italy in the 70s by Ribacchi [2]. In the 90s the Doorstopper method was practically abandoned for in situ rock virgin stress measurements and was substituted by other techniques, as hydraulic fracturing and triaxial cells overcoring.

For a virgin rock stress measurements the main drawbacks of the doorstopper were the limited maximum length of the borehole (about 10 m) and the requirement of at least 4 boreholes with different orientation for a reliable 3d stress tensor determination. But, at shallow depth, these limitations vanish at all.

Over the years, the Doorstopper technique has undergone some simple but significant improvements. The original version of the doorstopper cell with 3 strain gages, was substituted by a 4 strain gages version. In this way a single test allows statistical treatment of the data, making it possible to judge the test reliability and to estimate the confidence intervals for the computed stress components, for the principal stresses and for the principal directions. In the current version the cell has a temperature sensor, allowing thermal compensation of the measured overcoring strains. Standard strain gage bi-component glues are used, with curing time about half hour. The glue must be quite fluid, because it must form a very thin and regular film between the strain gages rosette and rock, when the cell is pressed against the borehole bottom. The plastic material forming the cell was studied in order to improve the quality of the test results. The plastic must have low stiffness, in order to not influence the strain measurement. But not too low: a too soft plastic may favour the formation of local thickening in the glue film, hindering the success of the test. Diamond cored borehole of size N (76 mm diameter) are used for the Doorstopper tests, drilled by a light hand electric machine (see the figure 1 as example).

![Figure 1. Executing Doorstopper tests at the top of a large tunnel lining. Using a light coring machine the stress test is an efficient and safe operation, carried out from a standard mobile lifting platform.](image-url)
An important improvement was the development of the RPR method for obtaining the longitudinal stress component [4]. But, this requires monitoring the deformation of the cell during the overcoring advance, and slows down dramatically the test execution. While the advantage of RPR method is big in virgin rock stress measurements, in shallow depth tests it is irrelevant, because the longitudinal stress component is negligible.

Generally a linear elastic isotropic approach is used for the test interpretation. In heterogeneous materials as concrete, it has been demonstrated by numerical simulations that the impact of heterogeneities tends to be of minor entity [4]. The ‘noise’ produced by the heterogeneity of the material can be minimized performing repeated test and averaging their results.

2.1. Theory of the Doorstopper overcoring Test at shallow depth

Let define a reference frame attached to the borehole (figure 2). The plane stress normal to the borehole axis, acting around the measurement point before drilling, is expressed in column matrix form: 

$$ [s] = [s_{xx} \ s_{zz} \ s_{xz}]^T $$

where $T$ means transposition.

Drilling and flattening the borehole bottom produces a local redistribution of the preexisting stress. The plane stress at the center of the borehole bottom is:

$$ [s'] = [s'_{xx} \ s'_{zz} \ s'_{xz}]^T $$

The relation between the bottom hole stress and the preexisting stress is linear:

$$ [s'] = [C] \ast [s] + [C'] \ast s_{yy} \quad (1) $$

where $s_{yy}$ is the preexisting stress component parallel to the borehole axis, $[C]$ and $[C']$ are the “stress concentration coefficients” matrices:

$$ [C] = \begin{bmatrix} C_n & C'_n & 0 \\ C'_n & C_n & 0 \\ 0 & 0 & C_f \end{bmatrix} \quad [C'] = \begin{bmatrix} C_l \\ C_l \\ C_f \end{bmatrix} \quad (2) $$

With homogeneous, isotropic and elastic materials, the non null terms of $[C]$ and $[C']$ are function of the Poisson ratio [4].

The cell measures the plane strain at the center of the borehole bottom produced by the overcoring:

$$ [\epsilon'] = [\epsilon'_{xx} \ \epsilon'_{zz} \ \epsilon'_{xz}]^T $$

From elasticity theory:

$$ [\epsilon'] = [D] \ast [s'] \quad (3) $$

where $[D]$ is a 3x3 matrix of elastic constants which terms are function of the Young modulus and the Poisson ratio.

The normal strain $\epsilon'_{\alpha}$ at an angle $\alpha$ from the x axis is given by a linear equation too:

$$ \epsilon'_{\alpha} = [A_{\alpha}] \ast [\epsilon'] \quad (4) $$

where $[A_{\alpha}]$ is a 1 x 3 row matrix function of the angle $\alpha$.

Combining and rearranging equations (1), (2), (3) and (4) gives:

$$ Y_{\alpha} = [X_{\alpha}] \ast [s] \quad (5) $$
where:

\[
[X_a] = [A_a] \cdot [D] \cdot [C]
\]

\[
Y_a = 4a - [A_a] \cdot [D] \cdot [C'] \cdot s_{yy}
\]

Applying equation (5) to the 4 strain gages of the doorstopper cell leads to a system of 4 linear equations in the 3 unknown stress components \(s_{xx}\), \(s_{zz}\) and \(s_{xz}\):

The preexisting stress parallel to the borehole axis \(s_{yy}\) is assumed to be known; in the case of shallow depth tests it is \(s_{yy} = 0\).

The system is overdetermined (4 equations in 3 unknown) and is solved by a multiple linear regression analysis.

2.2. Theory of the Radial Compression Test

A radial compression test measures the average Young modulus of the material.

When the material is isotropic the interpretation of the test is quite simple:

\[
E = (1 - \mu) \cdot \frac{\Delta p}{\Delta \varepsilon}
\]

(6)

where \(E\) is the average Young modulus, \(\mu\) is the Poisson ratio, \(\Delta p\) is the applied pressure, \(\Delta \varepsilon\) is the corresponding average strain of the cell’s strain gages.

It is strongly recommended to measure the elastic modulus with the same strain device used for overcoring, because this “local approach” provides a self-compensation of deviations from the theoretical behavior, in the overcoring and the radial compression test [4].

Much care must be devoted to minimize the gap between the radial cell and the instrumented head of the core. When it is impossible to set a null gap, a correction to the measured value of \(E\) must be applied [6].

Because the value of the Poisson ratio \(\mu\) has a low impact on the final test result, in most cases the value of \(\mu\) is assumed rather than measured; in most cases the choice is \(\mu = 0.2 - 0.25\).

A radial compression test gives always an important information on the tested material. See, for example, figure 3 where different materials are compared. The comparison of the first test (aluminum) with second (concrete) and the third (marble), suggests that the deviations from the theoretical behavior of a doorstopper test is practically only due to the material mechanical behavior. In the first case we note a negligible scatter between the 4 strain gages of the cell; in the concrete case the scatter is certainly due to the heterogeneity; also in the marble case, despite the appearance of the sample, there is a moderate scatter that could be explained with heterogeneity and/or local anisotropy.

![Figure 3. Some examples of radial stress tests](image-url)
3. Example 1: Sparvo Tunnel
During the period 2011-2013 two parallel tunnels about 2500 long were bored for the Bologna-Firenze highway. The tunnels are named Sparvo North and Sparvo South. They have a circular cross section with excavation diameter 15.5 m. The mutual distance between the North and South tunnels is 50 m. The maximum overburden is 250 m. The lining is made of precast segments of steel reinforced concrete. The longitudinal length of each ring of segments is 2 m. The radial thickness is 0.7 m. The space between lining and rock was filled by pea-gravel.

When the tunnels were completely bored, some evidence of high compression in the lining where observed. Any attempt to measure the virgin state of stress in the rock failed, due to the very low quality of the rock mass and of the rock materials. Most of the effort was concentrated in directly study the state of stress of the lining. The Dorstopper method was selected for various reasons: it allows the stress measurement at different radial depth within the lining thickness; it is suitable for high stress measurements; it produces a low disturbance on the lining; it is cheaper and more efficient than other techniques. Also the flat jack method was tested, but the stress level of the lining was often so high to close the cut during sawing operations, making impossible the jack insertion. Figure 4 shows the typical pattern of a measurement section.

Totally, the experimental study involved 618 stress measurements in 76 different lining rings with a number of test variable from 6 to 16 per lining ring. The circumferential stress component \( s_\theta \) (figure 4) was selected as the most significant results of the stress measurements.

![Figure 4](image)

**Figure 4.** Pattern of the stress measurements within a ring of the lining. The doorstopper tests were carried out at 5 different positions in radial drillings. For each position 2 stress measurements were performed: the first at a depth 15 cm, the second at a depth 45 cm.

The figures 6(b) and 6(c) summarize the distribution of the measured circumferential stress along the tunnel axis. The measured circumferential stress \( s_\theta \) varied between -0.7 MPa and 43.5 MPa \((s_\theta < 0 \text{ means tensile stress})\). Only in 3 cases on 618 the measurement gave a tensile \( s_\theta \). The figure 6 evidences a clear correlation between the results of the measurement and the geology. In both the tunnels there is a sector around the chainage 1750 m with a higher stress level, corresponding to the APA formation.

3.1. Interpretation of the collection of stress measurements of a lining ring
Despite the fact that a lining ring is a discontinuous set of concrete segments, a very simple linear elastic model was found to be effective for the interpretation of the tests collection performed in the same ring, as shown in the figures 6(d) and 6(e).

The interpretation of the ring is a typical inverse problem: given a collection of \( n \) measured circumferential stresses \( s_\theta \), find the initial stress of the model \( [\sigma] = [\sigma_{XX} \sigma_{YY} \sigma_{XY}]^T \) that best explains the measures. The experimental observations of the ring give a system of \( n \) linear equations:

\[
[s_\theta] = [X] \cdot [\sigma]
\]
where $[s_0]$ is the column matrix of the $n$ observed values, $[X]$ is a $n \times 3$ matrix of constants determined by means of the FEM model of the tunnel, while the 3 components of $[\sigma]$ are the unknown. Being $n$ a number between 6 and 16 (that is, the number of tests performed in a ring), the system is overdetermined and is solved by means of a linear multiple regression.

**Figure 5.** Finite Elements plane strain Model for the ring measurements interpretation, representing the lining and the surrounding rock. The nodes of the external boundary are restrained in X and Y. The lining is continuous. The FEM calculation has a unique stage: thus, the initial stress state $[\sigma]$ applied to the model should not be intended as the virgin state of stress of the rock but, rather, represents the fraction of the virgin stress that is supported by the lining. Between lining and rock there is a high stiffness contrast: $E_{\text{lining}} / E_{\text{rock}} = 200$.

![Finite Elements plane strain Model](image)

**Figure 6.** (a) is the geological profile of the North Sparvo Tunnel. The measured circumferential stresses are plotted in (b) and (c), where each marker corresponds to a doorstopper test. (d) and (e) show the values of the principal stress $\sigma_1$ computed in the interpretation of the lining rings; here each marker corresponds to a measurement lining ring.
Despite the apparent ingenuity of the adopted model, the result of the rings interpretation appears as meaningful. The figures 6(d) and 6(e) show the maximum principal stress $\sigma_1$ of the initial state $[\sigma]$. The comparison with the tunnel profile is clear, showing strong correlation of the measured stress level with the geology and with the overburden.

4. Example 2: Fior di Pesco Marble quarry

During 2017, following a request of the regional mining bureau, a stress tests campaign was started at the underground Fior di Pesco marble quarry named “Avanza” at Forni Avoltri, UD, Italy.

The geotechnical technicians decided to undertake some local Doostopper stress measurements in some critical points of the underground tunnels walls, where the highest stress were expected on the base of the preliminary FEM models of the quarry. The alternative option, a virgin stress measurement, was discarded. In this case the virgin stress, that is the stress state in some points of the rock not influenced by the underground excavations, was expected to be variable from point to point, due to the influence of the free surface. Conceptually, the “virgin stress approach” and the “local stress approach” were equivalent: both approaches requires the calibration of a numerical model on the measurements results. But the “local” approach gives also a direct measure of the stress level at some critical point of the excavations. Furthermore, it is cheaper and faster. The use of saw and diamond wire excavation methods, allowed stress measurement at shallow depth, because the disturbance at the underground walls was negligible (figure 7).

With reference to figure 8, during summer 2017 the first 3 stress measurements were performed. At each measurement point 2 repeated doorstopper tests were carried out. Immediately after, a commercial vibrating wire device for vertical uniaxial stress variations monitoring was installed at each measurement point. The goal of the stress variation instruments was to measure sudden stress variations due to the progress of the excavation, rather than slow drifts. At the end of 2019 the 3 installed stress variation devices gave a first measure. During summer 2020 other 2 local stress measurements were performed, followed by stress variation instruments installation. At the end of 2020, the instruments 4 and 5 gave a further stress variation measurement.
The current results of the stress measurement consist in 10 biaxial doorstopper stress tests and 5 uniaxial stress variation measurements at 5 different positions (tables 1 and 2).

Table 1. Results of the current doorstopper stress measurements. For the stress components ± means the 70% confidence limits. For the average $E$ modulus, ± means the relative standard deviation obtained with the radial compression test.

| Test | $\sigma'_{xx}$ [MPa] | $\sigma'_{zz}$ [MPa] | $\sigma'_{xz}$ [MPa] | $E$ [GPa] |
|------|----------------------|----------------------|----------------------|----------|
| 1.1  | 1.67 ± 0.40          | 6.95 ± 0.40          | 4.73 ± 0.27          | 96.8 ± 6% |
| 1.2  | 3.99 ± 2.85          | 9.31 ± 2.64          | 4.95 ± 1.84          | 79.7 ± 17% |
| 2.1  | 7.95 ± 1.02          | 11.68 ± 1.08         | 3.65 ± 0.72          | 95.0 ± 13% |
| 2.2  | 0.07 ± 0.87          | 11.65 ± 0.88         | 1.24 ± 0.61          | 82.2 ± 8% |
| 3.1  | 6.20 ± 1.55          | 18.65 ± 1.61         | -14.35 ± 0.98        | 95.0 ± 28% |
| 3.2  | -5.92 ± 2.87         | 20.76 ± 2.66         | -5.69 ± 1.80         | 76.4 ± 22% |
| 4.1  | -1.53 ± 1.42         | 5.88 ± 1.34          | 1.29 ± 0.88          | 80.7 ± 19% |
| 4.2  | 1.78 ± 1.23          | 2.54 ± 1.26          | -0.41 ± 0.79         | 100.0 ± 5% |
| 5.1  | 2.41 ± 1.43          | 13.06 ± 1.40         | 4.17 ± 1.00          | 63.4 ± 43% |
| 5.2  | 1.26 ± 2.69          | 8.64 ± 2.90          | 5.88 ± 1.93          | 59.9 ± 24% |

Table 2. Results of the current stress variation measurements.

| Test | $\Delta \sigma'_{zz}$ [MPa] | Time interval          |
|------|-----------------------------|------------------------|
| 1    | -10.9                       | June 2017 – November 2019 |
| 2    | -9.2                        | June 2017 – November 2019 |
| 3    | -11.2                       | June 2017 – November 2019 |
| 4    | -0.8                        | June 2020 – December 2020 |
| 5    | 0.0                         | June 2020 – December 2020 |

4.1. Interpretation of the collection of stress measurements
The 3d FEM model simulates, by a multistage calculation, the evolution of the exploitation tunnels from 2017 to end 2020, using 2 linear elastic materials: the marble and the surrounding rock (figure 9).
The inverse problem is: find the initial stress of the model \([\sigma] = [\sigma_{XX} \sigma_{YY} \sigma_{ZZ} \sigma_{XY} \sigma_{XZ} \sigma_{YZ}]^T\) that best explains the stress measurements.

The stress in the local frame \([s']_{(i)(j)} = [s'_{xx(i)(j)} s'_{yy(i)(j)} s'_{zz(i)(j)} s'_{xy(i)(j)} s'_{xz(i)(j)} s'_{yz(i)(j)}]^T\), computed by the model at the measurement point \((i)\) in the calculation stage \((j)\), is linear in \([\sigma]\):

\[
[s'] = [H]_{(i)} \cdot [\sigma_g]_{(i)(j)} = [H]_{(i)} \cdot [F]_{(i)(j)} \cdot [\sigma]
\]

being:

- \([H]_{(i)}\): the 6 x 6 tensor transformation matrix from (XYZ) to the local frame (xyz)\(_i\)
- \([F]_{(i)(j)}\): a 6 x 6 matrix computed for the point \((i)\) at the calculation stage \((j)\) by the FEM model
- \([\sigma_g]_{(i)(j)}\): the stress in the global frame due to the rock self-weight at the point \((i)\) in stage \((j)\).

With reference to table 1 note that, at each position, the 2 repeated doorstopper tests gave comparable results. Thus, at each position, we considered their average result; so doing, the bias due to unavoidable deviations from the theoretical behaviour is minimized.

The equation (7) can be used to write 3 doorstopper and 1 stress variation observations for each measurement point \((i)\). A doorstopper measurement involves the 1\(^{st}\), the 3\(^{rd}\) and 5\(^{th}\) rows of equation (7), corresponding to the plain stress components \(s'_{xx(i)(j)}\), \(s'_{zz(i)(j)}\), \(s'_{xz(i)(j)}\), measured at the calculation stage \((j)\). A uniaxial stress variation measurement between the stage \((j)\) and the stage \((k)\) involves the 3\(^{rd}\) row only, corresponding to the difference \(\Delta s'_{zz} = s'_{zz(i)(j)} - s'_{zz(i)(k)}\). Totally we obtain an overdetermined linear system of 20 experimental observations in the 6 unknown components of the initial stress tensor \([\sigma]\) applied to the model.

The system is solved by a least squares linear multiple regression.

After the solution, the model can also give an estimate of the stress \(s_{yy(i)(j)}\) parallel to the borehole axis at each doorstopper position \((i)\) at the calculation stage \((j)\). A iterative procedure with successive approximations, allows to take into account the effect of \(s_{yy(i)(j)}\). Anyway, this effect have a minor impact on the doorstopper tests interpretation: at maximum, about 1 MPa on the measured principal stresses.

Table 3 summarizes the result of the regression analysis. The Doorstopper 5.1 and 5.2 equations were excluded from the regression analysis because they disagree with the rest of the experimental data. An explication can be that tests 5.1 and 5.2 involved a material different from that of the other tests (see the E modulus values in table 1).

![Figure 9. Geometry of the FEM model. The nodes on the 4 vertical faces and on the bottom face are constrained in X,Y and Z. The contrast in stiffness between marble and surrounding rock is: 
\(E_{\text{marble}} / E_{\text{surrounding}} = 2.5\). The FEM reference frame is: X=North, Y=West, Z=Up](image-url)
We used a Montecarlo simulation approach for estimating the confidence intervals of the computed initial stress $[\sigma]$, with 10000 random extractions. A random extraction begins with the generation of a set of 10 doorstopper tests, starting from the average result and the covariance matrix of the 10 measurements. The average generated plane stress tensors for each couple of repeated tests is then computed. Then, a sample of the 5 stress variation measurements is random generated. For the stress variation measurements, a statistic analysis of the data is not possible. Thus, we assume a standard deviation equal to 10% of the measured value.

Table 3. Result of the interpretation of the collection of data. The first row reports the multiple regression estimate for initial state of stress of the model $[\sigma]$. The second rows reports the 70% confidence limits obtained by means of the Montecarlo simulation.

| $\sigma_{XX}$ [MPa] | $\sigma_{YY}$ [MPa] | $\sigma_{ZZ}$ [MPa] | $\sigma_{XY}$ [MPa] | $\sigma_{XZ}$ [MPa] | $\sigma_{YZ}$ [MPa] |
|---------------------|---------------------|---------------------|---------------------|---------------------|---------------------|
| 8.82                | 14.81               | 18.745              | -7.49               | 8.815               | -3.20               |
| +/- 1.51            | +/- 2.28            | +/- 5.61            | +/- 1.75            | +/- 1.775           | +/- 1.18            |

The plot of figure 10 compares the observed stress values and the corresponding values computed by the regression.

The adjusted multiple determination coefficient is high: $r^2_a = 0.90$. The good correlation of the data is satisfactory and encourage to continue with this approach.

It must not surprise that the model responds quite well, despite the apparent ingenuity of some assumptions as elastic homogeneous materials and uniform initial state of stress. The marble is in fact very blocky. The typical spacing of the fractures is 5-10 m and most of the visible fractures do not show any sign of movement. The surrounding rock, a fractured quartzite, is well represented by a lower $E$ modulus material.

Also, note that the maximum horizontal stress of $[\sigma]$ is approximately directed ENE-WSW. This agrees well with the information given by the World Stress Map project in that area [5].

Figure 10. Multiple regression analysis. The plot shows the comparison between observed values and computed values. The Doorstopper 5 equations are excluded from the regression analysis because they disagree with the rest of the experimental data.

5. Concluding remarks
In Italy, during the last decades, the Doorstopper technique has been successfully applied at shallow depth in several situations, for gaining high quality local stress measurements rather than difficult virgin rock stress measurements.
When the measurement involves linear, elastic, isotropic, non-fractured materials, as concrete or mechanically excavated low disturbed rock material, the stress tests interpretation is straightforward and reliable.

Frequently, a collection of punctual tests can be interpreted with a simple linear elastic numerical model, giving the interpolation of the punctual stress measurements and providing important information about the virgin stress field, as the maximum stress direction and its magnitude.

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