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# SOME QUANTITATIVE INVESTIGATIONS ON CURTAIN GROUTING IN ROCK FOUNDATIONS OF EARTH DAMS

# ALGUNAS INVESTIGACIONES CUANTITATIVAS EN CORTINAS DE INYECCION EN FUNDACIONES EN ROCA DE PRESAS DE TIERRA

Prof. Victor F. B. de Mello (1) - Eng. Paulo T. da Cruz (2)

Summary: Seeing that the literature on the subject shies away from any quantitative criteria, GEOTECNICA is engaged in a systematic collection of field data for the purpose of establishing such criteria for indicating when a grout curtain may be necessary, what the probable grout takes may be, and what benefits may be obtained. Starting from Lugeon's criterion, a new coefficient is shown to be preferable for registering results of water pressure tests in drill holes. The results of some investigations of fractured rock formations under compacted earth and concrete gravity dams are reported, and the subsequent grout takes and apparent improvements of the water-tightness of the rock within the grouted zone are correlated in a preliminary fashion. This information is submitted principally because of the promise that such rationalized method of collecting field data appears to offer of leading to important correlations for guidance to designers.

Sumário: Observando que la literatura no ha tratado este asunto bajo un criterio cuantitativo, la firma GEOTECNICA está empeñada en reunir sistemáticamente datos de campo con el proposito de estabelecer tal criterio para indicación de cuando una cortina de inyección es necessaria, la tomada de lechada probable, y los beneficios que pueden ser obtenidos. Partindo del criterio de Lugeon, un nuevo coeficiente ha demostrato ser preferible para registrar los resultados de los ensayos de pressión de água en perfuraciones de sondeo. Fueron presentados los resultados de algunas investigaciones de formaciones de roca fracturada bajo presas-de tierra compactada y de gravedad de concreto, y fueron correlacionadas de una forma preliminar las subsecuentes tomadas de lechada y las aparentes mejorías de estanquidad al água de la roca en la región inyectada. Esta información fue presentada principalmente debido a la promesa que algunos de tales métodos racionalizados de colleccionar los datos de campo parecen ofrecer, llevando a importantes correlaciones destinadas a guiar los proyectistas.

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(1) Director of Works; (2) Engineer, GEOTECNICA S/A. - Engenheiros Consultores

Introduction: In a great many dams considerable sums of money are spent in providing so called cut off grout curtains in rock foundations. Little seems to be known, however, in a quantitative way about the necessity of such treatment, the possibility of estimating the grout takes that affect the cost of it, and particularly, about the benefits that may be derived therefrom. This state of relative ignorance is in some ways comprehensible because the subject is tied to typically heterogeneous natural conditions, involves rock materials which geologists customarily have not investigated for quantitative behaviour, and usually the information on the behaviour of the foundations of the dam only becomes available in a rather scant manner, if at all, and quite some time after completion of the structure. It is felt therefore that a concerted effort should be made by civil engineers associated with this field, to accumulate systematic data which may within a few years permit satisfactory estimates to be made during the design phase. The test methods and preliminary interpretations that are furnished herein may serve as a basis for rationalizing the collection of data, the final test of which will only derive from actual observation of the behaviour of structures under working conditions.

Survey of literature on the subject: Among the numerous papers, construction reports, and job designs and specication, that can be found with direct or indirect reference to the subject, most are found to fall appropriately within the following groupings. Some discuss equipment and techniques of grouting without furnishing evidence that the technique considered preferable does achieve better results; for instance, multiple - or single-line grouting, stage - or packer grouting, and other such different procedures are stated as preferable, but no data are published (besides the obvious economic factors) to give support to such preferences (1,2,3,4,5,6,7,8,9,10)*. Some describe completed jobs, furnishing merely data on commercial items such as total length perforated and number of bags of cement injected; usually it is stated that the results were satisfactory, but it is not known how such a conclusion was reached, since conditions before and after grouting are not compared, and the impression seems to be conveyed that the bigger the grout take, the more satisfactory the grouting job. (7,11,12,13). Some mention special admixtures, chemical and otherwise, that are claimed to be beneficial but the data are not made available, either on the detailed composition of the grout or the proof of its comparative value. (8,11,12,14,15,16,17). Yet some publications are guided by a worthwhile preoccupation for the study of individual physical properties of the grouts, grout

* These numbers correspond to references listed at the end.

ing pressures, size of fissures, etc. but it must be conceded that the results of these investigations are yet a long way from furnishing the type of guidance that design engineers require for practical cases (14,16,17,19,20,21,22). Other available literature derives from case-histories which commendably supply details of the grouting specifications applied, but are scant in relating the bases for establishing such specifications (10,15,26-31,32-36). Finally and in short, with very rare exceptions (e.g.37) no mention is encountered of the quantitative criteria used to establish the necessity of a grout curtain in rock, its design details and the real efficacy of the treatment.

Water pressure test: Although it must be recognized that the use of small-diameter drill holes to investigate the characteristics of a rock mass is subject to criticism, it is felt that no visual observations can rightly substitute for quantitative testing (cf. 9) and if the test is considered poorly representative the right approach is to improve its individual details or the program that comprises it. It is our opinion that under normal conditions of moderate to fine fissures the 2" diameter (AX) is satisfactory for the testing of the perviousness of a rock, and that it is better to investigate the rock formation by several such holes - rather than by holes of larger diameters in smaller numbers for the same total cost. In the dams for which we conducted the design investigations, including about 10-15 such holes, and subsequently conducted or supervised the curtain grouting involving about 10-20 times as many holes, no discrepancy at all was found between the early conclusions and the overall results. The following procedure has been used and is herewith recommended as apparently satisfactory. The drilling is interrupted roughly every three meters, or at smaller intervals if open fissures are revealed, in order to run a series of water-loss tests. At the top of each new increment of perforation a suitable packer is adjusted: the leather-cup, the expanding-bladder, or expanding-solid-rubber-cylinder types have been used sucessfully depending on the roughness of the hole. Thus the tested length is usually about 3 meters, from the packer to the bottom of the hole. After the last of such tests the packer is finally set at the top (first position) and the overall length of hole is tested. At each position of the packer at least three test pressures should be used for separate runs. The first pressure is such as to avoid any possibility of uplifting the rock. The maximum gauge pressure should be $q \leq (\gamma - 1)x + (\gamma - 2)y$ where $\gamma$ is the assumed unit weight of the rock ($\simeq 2.5 t/m^3$ as a safe estimate), $x$ is the depth to the natural water level, and $y$ is the depth of the packer below this water level (Drw.1). After satisfactory flow measurements have been obtained, as described below, the pressure is increased, to a value of roughly 75% of the head corresponding to the difference between the natural ground water elevation and the maximum future reservoir water level. Finally a third run is made with approximately twice the above pressure. The water losses under the lowest test pressure are believed to furnish satisfactory indication of the previousness of the rock. The second and third tests are meant to investigate conditions of possible uplift downstream of the dam and simultaneously to evaluate the possibility of applying reasonably high grouting pressures without damage to the rock.

The flow measurements should be made in sufficiently long periods so as to reach approximately constant readings We would recommend readings every 5 minutes for a minimum of 15 minutes, or more (up to about 30 mins.) if constant readings are nor achieved. Obviously this time would not be sufficient for due investigation of the more impervious materials (equivalent permeability less than $10^{-4}$cm/sec.), but in such cases the investigation need not be carried further. A hydrometer reading with a precision of 1 liter or better should be used.

The results of these tests are computed in the form of a "coefficient of water loss" as liters per minute per meter of hole per unit pressure (kg/cm$^2$, or approx. atmosphere). The pressure used is the net pressure applied at the mid-point of the tested length, as indicated by $p_1$, $p_2$, $p_3$ etc. in the pressure diagram of drawing 1.

For greater clarity of presentation the computed coefficients are drawn on a semi-log plot (Drw.1).

One interpretation of considerable interest is immediately apparent from a comparison of the values of these coefficients for the same stretch of hole and for different test pressures. It has been consistently observed that this coefficient normally decreases slightly with the increase of pressure, as appears to be reasonable under the assumption that flow is not laminar. It is therefore possible to detect forthwith when the applied pressure results in an opening of the fissures, since the coefficient of water loss thereupon increases noticeably at the higher pressure. In the example shown on drawing 1 the 7kg/cm$^2$ pressure caused such an opening of fissures in the second test-length: the grouting pressures in this case should not exceed 5 kg/cm$^2$.

A unit coefficient of water loss (1 liter per minute per meter per atmosphere) corresponds roughly to an "equivalent permeability coefficient of a homogeneous and isotropic material" of the order $1 \times 10^{-4}$cm/sec., for the test conditions above recommended.

Criteria for evaluating the necessity of a grout curtain: The best known criterion for establishing the presumed need for a grouting by means of water pressure tests in drill holes in the Lugeon criterion (37). The drill hole has a diameter of 46-76mm and is tested in 1-2 meter lengths. The empirical rule states that the foundation is sufficiently impervious (to dispense with any grouting) if the water loss does not exceed 1 litre per minute per meter, under a pressure of 10 atmospheres maintained for 10 minutes. The "unité Lugeon", UL, is such a water loss of 1 liter per minute per meter, which would correspond to 0.1 units of our coefficient of water loss, or roughly to an equivalent permeability coefficient of $10^{-5}$cm/sec. A slightly less severe criterion (2 UL) has been used in several of the high arch dams in Portugal (38), and for dams smaller than 30m Lugeon accepts 3 UL as the limit (39). It should be conceded, however, that all these values are of the same order of magnitude for practical purposes. And it should be remembered that these empirical rules are meant to reflect principally the European experience on masonry and concrete dams, although their use is quite widespread (40,41).

Apparently therefore a foundation rock that gives a coefficient of water loss smaller than 0.1 lit/min/m/atm. will not be grouted even when the dam that rests on it is an arch dam with a base width as low as 12 to 15% of the height. Should the same limit be applied to a foundation rock upon which it is proposed to build a homogeneous compacted clay dam with an effective base width (between the upstream toe and the nearest probable drainage line under the downstream half) of 3.5 to 4 times the height? It is obvious that under entirely analogous conditions the seepage loss under such a dam might be no more than about 5% of the seepage under the corresponding arch dam, but it must be recognized that "the hazard associated with seepage at dam sites has little if any relation to volume of water loss" (Walker, 42). Thus, although it is recognized in earth dam design that seepage losses through foundations with permeability coefficients of the order of $10^{-4}$cm/sec (approximately 1 lit/min/m/atm of coefficient of water loss) are of no concern, some type of protection for underseepage is indubitably applied in such cases, preferably by relief wells (and, in some instances, by curtain grouting - e.g. 43).

The following suggestions attempt to embody reasonable adaptations of present criteria into working rules for average conditions; all criteria are based on coefficients of water loss:- (a) No treatment should be necessary for dams of the narrowest "impervious" base widths (approx. 20% of the height) if the foundation rock yields coefficients smaller than 0.3 lit/min/m/atm for dams under 30m, 0.2 for dams between 30 and 100m, and 0.1 for dams higher than 100m; b) For dams with wider impervious base widths the above limiting coefficients may be increased in proportion to the increase of the base width until a maximum coefficient of 1.0 lit/min/m/atm; (c) In all cases, foundation rock with coefficients higher than 1.0 must be carefully considered with regard to requiring both a drainage system and a sealing system (blanket, positive cut off by trenching and refilling or grouting); (d) For intermediate cases, either an effective drainage system or an effective sealing system may be selected.

The above suggestions must be promptly qualified insofar as no such numerical limits should ever be applied without careful consideration of the individual case. A reasoning for rock perviousness based on average effective permeability coefficients may lead to the grossest mistakes if the rock is not massive and moderately isotropic. Geologic and test evidence on the preferential seepage paths within the rock should be very carefully judged: for instance, unless such precautions are taken, a single widely open joint responsible for most of the water loss may not be detected by drilling a sufficient number of test holes and by running the pressure tests over various stretches of different lengths: they may also be foreseen or explained by geologic reconnaissance of the formation.

Our present experience is limited to gneisses, granites, diabase dikes, siltstones, quartzites, and silicified siltstones in none of which have we yet encountered major irregularities. It may be observed, however, that in items (b) and (c) of the above working rules we have been influenced by the fact that whenever a coefficient higher than 1 is encountered, some important open joint may be indicated.

<u>Grout takes and efficiencies of grout curtains</u>: It has been found that the use of the coefficient of water loss may be satisfactorily extended to the case of a "coefficient of grout loss" (lit/min/m/atm) and that some empirical correlations may be established between the two, for each water-cement ratio. Further, by taking into account the probable viscosities of the various mixes (19) some empirical correlation may yet be established between the two coefficients, independent of the mix.

Drawing 2 gives sample evidence of the type of correlation that may be sought in this connection. Both cases refer to a gneiss grouted under fairly routine procedures:- AX holes spaced 2-3m center-to-center, grouted under pressures ranging from 2 to 5kg/cm$^2$, with grout mixes of 10:1 to 1:1 (water:cement, by volume); a part of the program was conducted by stage grouting, and later it was changed to packer grouting.

In both cases, the computations on the grout take (left half of the graph) are based on all the grouting data since every grout hole was first pressure tested. Each plotted point represents an average of a group of 10-15 contiguous holes. The right half of the graph is naturally obtained from much fewer holes inasfar as concerns the presumed benefits achieved by the grouting program, since at best each zone comprising 10-15 grout holes was checked by a single testhole.

Some of the principal conclusions derived from these studies are as follows:

a) in such rocks, when the coefficient of water loss is less than 0.1 lit/min/m/atm the grout take is altogether negligible. We are therefore inclined to inquire if Lugeon's limit was not established basically by reference to what water losses are indicative of groutability, rather than by determination of what cases require grouting.

Under such conditions a grouting job appears to be highly inefficient because of the high drilling costs associated with very small grout takes.

b) Under the pressures and mixes used, the radius of action of each grout hole appears to be of the order 2m (barring special cases of wide-open joints) since the coefficients of water losses and of grout takes of the holes were all essentially alike, until spacings smaller than approx. 4m were reached, even if contiguous holes had already been grouted (split-spacing technique).

c) The average improvement ratio appears to be of the order 5 - (ratio of the coefficient of water loss before grouting and the same coefficient after grouting, suggested by Kravetz, 17). Thus for instance in Case II an initial coefficient of water loss of 1.0 leads to a coefficient of grout take of about 0.5 (left half of the drawing) and this grout take leads in turn to a reduction (improvement) of the coefficient of water loss of the order of 0.8 (right half of the drawing); that is the final coefficient of water loss within the grouted mass will thus result of the order of 0.2.

Such correlations are believed to contain the type of guidance that designers require:- a possibility of estimating the total cost of a proposed treatment, in order to compare it with other alternatives, and a possibility of evaluating the efficacy of the treatment itself and of some of its design details capable of affecting the final results.

One important fact becomes immediately apparent from the above data is that the overall benefits of a narrow grout curtain are vastly overestimated in general. Consider the case of a 50m homogeneous compacted clay dam of 1:3.5 upstream slope, resting on a rock formation free of any geologic peculiarities affecting seepage; assume that there is a line of filter wells and horizontal filter at the downstream edge of the middle third of the downstream section (of slope 1:3). The overall seepage path through the rock will be of the order of 5.5 x 50m, that is 275m. If the initial coefficient of water loss is of the order of 0.5 lit/ /min/m/atm, many designers would call for a grout curtain, under present-day published recommendations. The final coefficient likely to result within the grouted mass will be of the order of 0.1 lit/min/m/atm. Therefore, if a single line of grout holes is used and thereby a grouted mass 4m wide is achieved, these 4m of material with a coefficient of 0.1 should produce roughly the same head loss as 20m of the initial material of coefficient 0.5. Thus, such a single-line grout curtain would be tantamount to adding about 20m to the initial seepage path of 275m obviously a very small improvement indeed.

Careful consideration should therefore be given to the width that must be given to the grout curtain. This item has often been overlooked because of the vague impression that grouting can achieve an "absolute" water barrier. It should be fully recognized that no such perfect condition is possible.

## Conclusions

An appeal must be made for the systematic collection and publication of quantitative data on water pressure tests before and after grouting, and on grout takes (evaluated in a fashion analogous to the water losses). A coefficient of water or grout loss in liters per minute per meter per atmosphere (in AX Holes) appears to be satisfactory. The results collected by our organization within a very short period lead to the hope that very satisfactory correlations may be reached. Barring the cases involving special geologic peculiarities, our results lead to the impression that many grout curtains are used in conditions where very little overall benefit is derived.

## Conclusiones

Debe ser hecha una petición para la colección y publicación sistemática de dados cuantitativos en ensayos de perdida de água antes y despues de la inyección, y en tomadas de lechada (apreciados de una forma analoga a las perdidas de água). Un coeficiente de água o perdida de lechada en litros por minuto por metro por atmosfera (en taladros AX) parece ser satisfactorio.

Los resultados reunidos por nuestra organización durante un periodo muy corto nos dan esperanza de que correlaciones muy satisfactorias pueden ser obtenidas. Exceptuando los casos que envuelven peculiaridades geológicas especiales, nuestros resultados conduzen a la impresión de que muchas cortinas de inyección son usadas en condiciones donde resulta muy poco beneficio.

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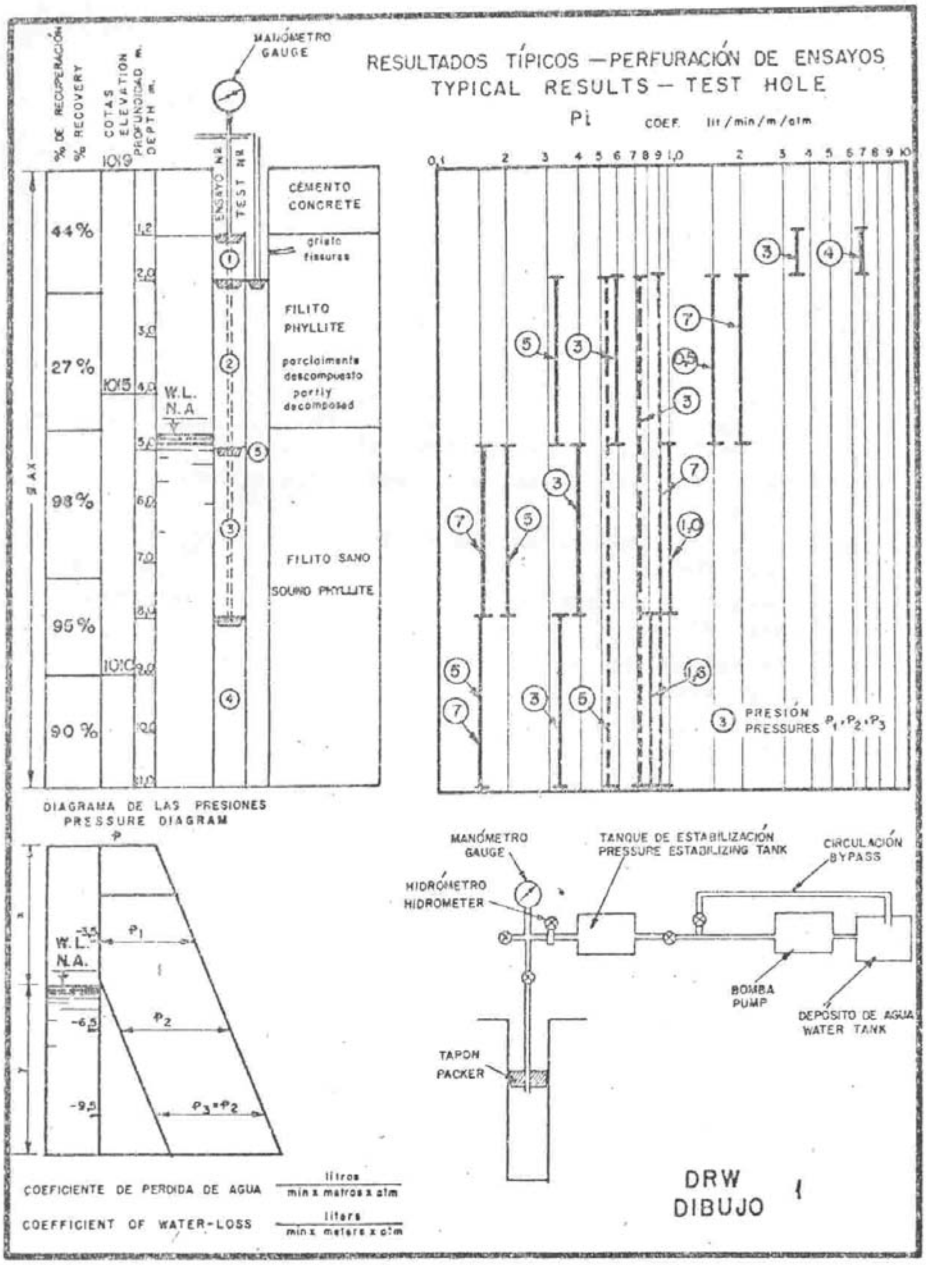
RESULTADOS TÍPICOS — PERFURACIÓN DE ENSAYOS
TYPICAL RESULTS — TEST HOLE
% DE RECUPERACIÓN
% RECOVERY
COTAS ELEVATION
PROFUNDIDAD m. DEPTH m.
ENSAYO Nr TEST Nr
MANÓMETRO GAUGE
CÉMENTO CONCRETE
grieta fissures
FILITO PHYLLITE
parcialmente descompuesto
partly decomposed
FILITO SANO
SOUND PHYLLITE
W.L. N.A
44%
27%
98%
95%
90%
Pi COEF. lit/min/m/atm
PRESIÓN PRESSURES $P_1, P_2, P_3$
DIAGRAMA DE LAS PRESIONES
PRESSURE DIAGRAM
$P_3 = P_2$
TANQUE DE ESTABILIZACIÓN
PRESSURE ESTABILIZING TANK
CIRCULACIÓN BYPASS
HIDRÓMETRO HIDROMETER
BOMBA PUMP
DEPÓSITO DE AGUA WATER TANK
TAPON PACKER
COEFICIENTE DE PERDIDA DE AGUA litros / min x metros x atm
COEFFICIENT OF WATER-LOSS liters / min x meters x atm
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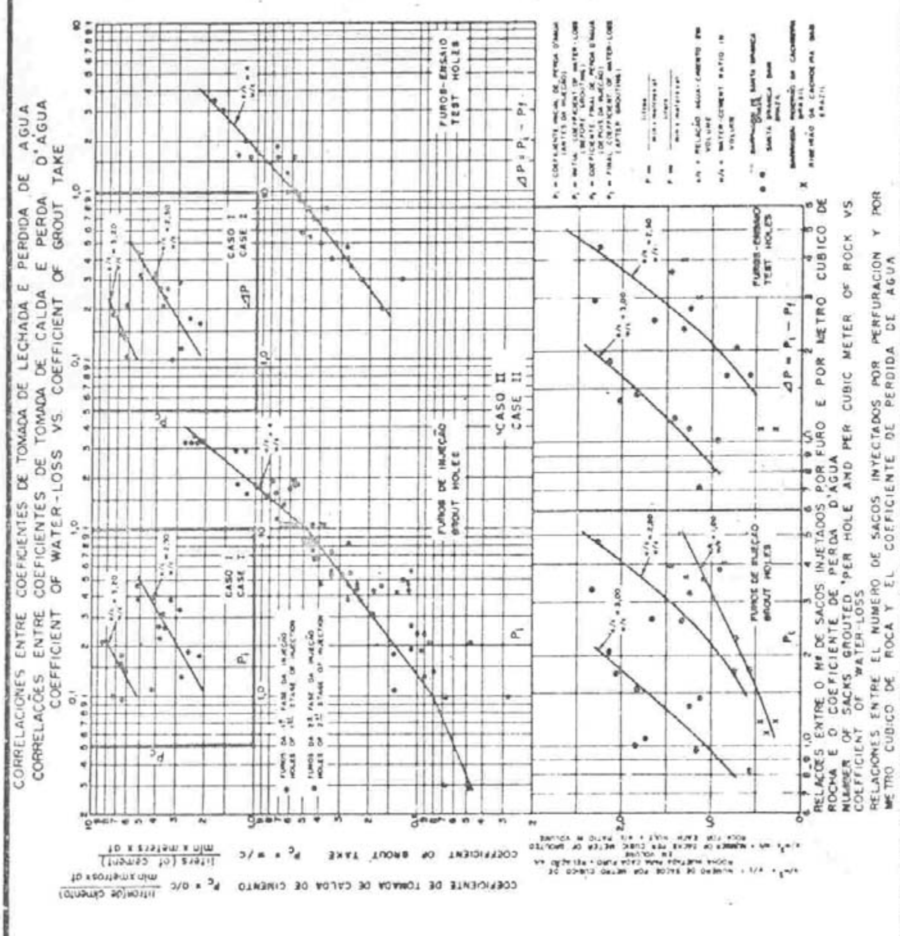


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