LAND SUBSIDENCE EFFECTED BY DEWATERING OF OPEN-PITS

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ABSTRACT

In 1975 the construction of one of the world biggest lignite open-pits, the Bełchatów-pit, was begun in central Poland. Opening out required the prior drainage of the overburden. At present the cone of drawdown extends for about 10 kilometers and the maximum drawdown of the groundwater level in the pit is about 200 meters.

At the same time as dewatering began, a survey of the influence of drainage over the neighbouring area was started. More as 3000 ground movement points are surveyed. Up to now the maximal subsidence 0,5 m has been recorded.

Two theoretical interpretative models of the subsidence process are applied. The first model was based on Terzaghi's uniaxial consolidation theory. In the second one it was assumed that the true process deviate from Terzaghi's principles due to the rock mass anisotropy.

The survey results enabled the verification of both models. The approximation procedure was applied to determine corrective coefficients expressing errors of the model parameters and processes not contained in the models.

This model together with corrective coefficients enables the detail forcasts of land subsidence around openpit and dewatering operations.

INTRODUCTION

The dewatering of surface mines brings about lowering of groundwater level in the environment. The ground subsidence is one of the result of this lowering, which can involve damage to the objects located in this area. A similar process occurs in the area of water intakes and during oil-field and natural gas development. The international symposium in Tokyo in 1969 was a proof of interest in this process.

The ground deformations are also associated with open-pit development and removal of earth mass on to external dumping space. It is manifested by horizontal movements towards the open-pit and by elevation of slope surfaces and ground strip adjacent to open-pit upper edge (Gloe 1979, Wojciechowski and Kasza 1984).

These processes are superimposed on to another. That is why the geodetic surveying enables to control the final effect only, without possibility for their causes to be separated.

SURVEY OF THE BEŁCHATÓW OPEN-PIT SITE AREA

In 1975, in central Poland, the construction of one of the biggest surface lignite mine in the world began. Nowadays, the range of indispensable drainage of rock mass exceeds 10 km, and the greatest depression of groundwater pressure amounts to about 200 m.

Simultaneously with drainage operation, the geodetic surveying of adjoining area have begun. This area is flat and land development is dispersed, thus providing especially favorable observation conditions. About 3000 bench marks are observed on the area of dozens thousand hectares.

Contrary to the simple relief, the geological structure of Bełchatów deposit is very complicated. The coal seams occur in a deep fault trough and a number of faults intersect their raised wings (Braniecka and others 1981, Wojciechowski and Kasza 1984).

An opinion become generally accepted that final size of ground subsidences results mainly from final depression and depth of occurence of slightly deformed bedrock but the course of depression in time, and filtering properties of soils decide on the course of subsidence in time.

The results of geodetic surveying of subsidences have confirmed this opinion in general. In the region of fault trough where the bedrock (Mesozoic) occurs at a depth of 250-350 m the greatest subsidences have taken place in the vicinity of the drainage centre. Beyond the limits of fault trough, the subsidences are less, and they disappear outside the reach of cone of depression (fig. 1).

PROBLEM OF A PROGNOSTIC MODEL

An intensive land development around the pit requires prediction of ground subsidences. Considerable subsidences can change slopes of ditches and pipelines. The important differences in subsidences which can be expected over the faults of rockbed can have an destructive influence on buildings. Therefore, a necessity arose to work out a mathematical model which could describe both previous and future course of ground subsidence process with technically admissible errors. There are two types of such models in use (Dmitruk and Lysik 1978, Dmitruk 1984):

- models basing on the principles of mechanics, mainly principles of soil mechanics in this case, called further on "models of mechanics",
- analog models taking into account general trends resulting from of the principles of mechanics.

The feature of analog models which makes them different from models of mechanics is to define parameters of model basing on external effects of the process (indices of the process) measured at a real object.

Often applied mathematical models based only on the statistics give no reason to a forecast which is far ahead of the observation period.

For point-wise observation of subsidences, in order to work out and verify the models, the following data are necessary:
- lithological profile (geometric parameters),
- soil properties in particular layers (material parameters),
- changes in groundwater pressures (load forcing subsidence),
- ground subsidence (index of the process).

The data concerning subsidences of particular layers would be very wishful to verify a model but they would require deep-seated bench marks to be installed . The high cost of such bench marks makes their common application impossible.

The data indicated as necessary can be obtained from three sources. The lithological profiles are defined in a regular network of boreholes 500 x 500 m spaced more closely in the developing cout to 125x125 m, and most sparsely outside the deposit, within the reach of predicted cone of depression. The soil properties are examined only in some holes.

The pressures of water are measured in piezometer network whose arrangement is imposed by reasons of dewatering efficiency control. As a rule, they are situated along the radii coming out from the centre of developing cut.

The subsidences are measured at bench marks of levelling network whose arrangement and density is imposed by the needs of mining operations, and civil engineering works, and by conditions of bench marks protection against damage.

Only exceptionally, the prospecting hole, piezometer and bench mark are situated at one point. Especially piezometers are situated at considerable distances from the nearest points of two other networks. In order to determine all required parameters at the point of bench mark geological, geotechnical and hydrogeological interpretation is necessary with its inevitable subjective approach and related errors.

TERZAGHI'S MODEL

As interpretative-prognostic model, a model has been accepted basing on the Terzaghi's theory of uniaxial consolidation, conventionally called from his name. It is described by equations (Poland 1970):

$$S\ (t) = \sum_{i=1}^{n} \int_{z_{i-1}}^{z_i} \frac{u_{oi} - u_i}{M_i}\, dz \qquad (1)$$

$$c_v \frac{\partial^2 u}{\partial z^2} = \frac{\partial u}{\partial t} \qquad (2)$$

where:

$S\ (t)$ - calculated, from the model, subsidence of examined ground point in time t measured from the beginning of dewatering,

$M_i = \frac{1}{m_{vi}}$ - compression modulus of the layer i,

u_{oi} - initial pore pressure at point z of layer i,

u_i - pore pressure at the same point in time t, determined from equation (2)

z_{i-1}, z_i - depth of the roof and floor of layer measured from primary groundwater table,

c_v - coefficient of consolidation (hydraulic diffussivity).

The sequence of layers allows to accept such a model. The layers of cohesive soils (consolidated layers or aquitards) are separated, as a rule, by the lavers of sands and gravels where filters of drainage wells are placed (draining layers or aquifers). However, there are cases of aquitards complexes lying directly one on another. In such cases, the whole complex is considered as one conventionary layer. An example of such a complex are coal and coal-bearing clay layers.

The continuous-in-time changes of pressure in the acquifers are replaced by step changes corresponding to the determined time intervals. For calculation, a special computer program has been worked out.

The material characteristics encountered in the model are accepted basing on the the results of laboratory testing made by the Establishment of Geological Works of the Warsaw University whithin the range of pressures from 0,05 to 2,5 MPa.

The compression moduli obtained from consolidometric tests are approximated by a lineai function (fig. 2) according to the commonly known results of Terzaghi's investigations:

$$M_i = A_i C'_z + B \tag{3}$$

The coefficients of correlation included in the range 0,75-0,90 can not be considered as satisfactory, particularly in relation to the necessity of extrapolation of the results to presures of about 5 MPa and more. The unreliablility is increased by a critical estimate of the principle itself of consolidometric testing. Wiłun (1972), basing on the numerous observations of building subsidences, put forward a hypothesis that real compression moduli are much more in excess of values obtained from testing, and he suggests to multiply these values by correction factors attaining 3 and more. However, the range of values M<30 MPa under investigation of Wiłun did not allow to use a table of these factors. Consequenetly, a conclusion can be drawn that compression moduli are an unreliable parameter of the model.

Even more unreliable are consolidation coefficients obtained from similar testing. Few and scattered results constrain to accept computational values in a way of evaluation controlled by a comparison with the results given in the literature.

Finally accepted analytical values are summarized in table 1.

Table 1. Accepted material characteristics of Terzaghi's model.

Type of soil	A 1	B_k MPa	c_{vk} m^2a^{-1}	γ_k MN m^{-3}
Sands	200	40	0	0.018
Loams	43	6	50	0.021
Silts	47	11	20	0.020
Clays (fissurated)	35	9	50	0.021
Lignite	22	8	20	0.015

VERIFICATION OF TERZAGHI'S MODEL

For verification of the model, a set of 36 bench marks has been selected. A criterion for the selection was reliability of data.

It became evident that the subsidences S (t) calculated from the model are twice as large as measured subsidences P (t) on the average. It can be admitted to be a confirmation of Witun's hypothesis but in order that one may burden only compression moduli with this discrepancy more extensive investigation should be carried out to justify such an opinion. After all, one can also suppose that a cause of discrepancy are too high values c_v. So, the model under consideration can not be used for prognosis.

In order to achieve a prognostic model, a correction function has been introduced:

$$S' = K_1 \cdot S + K_2 \approx P \tag{4}$$

where:

K_1 and K_2 are simple regression factors interpreted to be:

K_1 - correction factor,

K_2 - constant for discrepancy to characterize processes being not described by the model.

The model supplemented in such a way loses features of a model of the mechanics, and it approximates to the model - analogue. The obtained values of the factors are summarized in table 2.

Table 2. Parameters of correction function.

Characteristic	Year of observation t a	1979 4	1981 6	1983 8
1		2	3	4
mean value P (t)	mm	79	135	163
mean value S (t)	mm	168	261	314
correction factor K_1	1	0,407	0,476	0,482
constant K_2	m	25	79	39
correlation factor $r_{S,P} = r_{S',P}$		0,76	0,79	0,76

An increase of values K_1 and K_2 with time is worthy of notice. It brings in question the utility of supplemented model for a long term prediction, despite a reduced rate of increase in the factors lately.

Considering simultaneous increase of K_1 and K_2, a conclusion can be drawn that the replacement of twoparameter function (4) by single-parameter one (K_2=0) would not considerably affect the correlation factors which, however, can not be scarcely considered as satisfactory.

VERIFICATION IN THE REGIONS

A supposition arises that low correlation factors can result from the use of one function S' for the regions of different geological structure. Perhaps, better correlations would be successful to achieve by dividing the whole area in geological regions representing some types of the structure. The division is made as follows:

Western region (zone ahead mining operations) - fault trough, alternate layers of sand and cohesive soils with prevailing sands in the upper part of profile (Quaternary) and cohesive soils in the lower part (Tertiary), coal complex of about 60 m, subsoil constituted by Mesozoic rocks at depths 270-320 m (8 bench marks).

Eastern region - the structure similar to the western region, coal complex up to 40 m occurring locally.

North-eastern region - erosion trough with prevailing sands in the profile to a depth of 100 m, subsoil at a depth of 210-300 m.

Northern region - Mesozoic bedrock occurs at a depth of 80-200 m below grade. Quaternary of a thickness of about 80 m are alternate layers of sand and cohesive soils. In the Tertiary, there are contained sands and clays with coal intercalations.

Southarn region - prevailing sand in the profile, bedrock at depth from 60 to 100 m.

The obtained parameters of correction function for the regions are given in table 3.

Table 3. Parameters of correction function after dividing into regions

Year of observation	Characteristic		P t mm	S t mm	K_1 1	K_2 mm	$r_{S,T}$ 1
Eastern region 7 bench marks	1979	4	92	149	0,435	38	0,77
	1981	6	148	257	0,417	31	0,72
	1983	8	185	360	0,481	31	0,79
North-eastern region 7	1979	4	86	152	0,447	30	0,79
	1981	6	128	206	0,462	27	0,84
	1983	8	161	297	0,488	29	0,84
Northern region 12	1979	4	53	100	0,414	22	0,76
	1981	6	92	191	0,410	31	0,71
	1983	8	131	276	0,402	37	0,75
Western region 8	1979	4	77	114	0,515	29	0,82
	1981	6	132	200	0,505	35	0,86
	1983	8	193	320	0,506	39	0,86

As can be seen the regionalization improves correlation only in the Western region but in no one of the regions, a distinct increase of K_1 and K_2 is visible in the same time.

WEAK SIDES OF TERZAGHI'S MODEL IN USE

A very important parameter of the model is thickness of aquitards. As is often the case, drilling does not find sandy intercalations in thick cohesive soil layers and then, the real thicknesses of aquitards can be significantly smaller than those assumed in the model. It involves errors in value S(t). In case of high thicknesses and low values C_v, these errors can predominate.

So, if there is no certainty as for the sequence of layers, better results can be obtained from a simplified model-analogue where such a profile will be hidden in the parameters being determined in the identifying procedure of the model.

MODEL - ANALOGUE

Just as in the model described above, the continuous decrease in water pressures is replaced by a step decrease with steps depending on the required accuracy of calculation and disposable data.

It is assumed that every conventionary layer corresponding to a step of depression at equal time intervals settles with a delay characterized by time factor:

$$\varkappa_j(t) = 1 - \exp\left[-\alpha(t-t_j)\right] \tag{5}$$

where:

t_j - time from the beginning of drainage to the moment of jump

α - parameter to be found in identifying procedure of the model.

The subsidence at the moment t will attain:

$$S(t) = \sum_{j=1}^{m} \sum_{i=1}^{n} \frac{U_{i,j-1} - U_{i,j}}{M_i} (z_i - z_{i-1}) \mathcal{K}_j(t) \tag{6}$$

where:

- i - number of computational layer,
- n - number of layers from primary water table to the bedrock,
- m - number of conventionary jumps of depression before a moment t but no more than until achieving bedrock,
- M_i - compression modulus determined for the centre of layer i,
- $U_{i,j-1}$, $U_{i,j}$ - water pressure in the middle of a thickness of layer i before and after jump j.

Other designations - as previously.

The linear increase of compression modulus with the depth is assumed otherwise than for the Terzaghi's model:

$$M_i = A' \frac{Z_{i-1} + Z_i}{2} + B \tag{7}$$

Basing on the field investigation, many authors declare themselves for such a relationship (fig. 3, Kezdi 1964).

IDENTIFICATION OF MODEL PARAMETERS

The identification of model parameters consists in the selection of such parameters A, B that, considering permisible errors,

$$S(t) \approx P(t) \tag{8}$$

in each time t when P was measured.

In practice, such a problem is impossible to be solved without a simplifying assumption that parameters A', B, are constant in the whole profile.

However, even at such assumption, a dificulty arises as illustrated by the theoretical example presented in fig. 4. The linear increase in groundwater depression up to the subsoil during five years has been assumed, and stationary depression in next years as well.

As can be seen, the increase α involves a deflection of the subsidence line downwards. A similar effect is also coused by the increase of parameter A. Hence, it will be difficult to identify each of these parameters separately for individual bench mark. It will be possible only to identify a set of pairs of these parameters, and each pair will satisfy the condition (8). The best pair will be possible to select from the set of bench marks with different depths of the subsoil and different advance rate of dewatering process if similar lithological profiles are the case. For the present, there is lack of a wide experience in the identifying technique. It seems that the following procedure should be suggested.

In the region characterized by a given type of geological structure, several bench marks are selected having most reliable and most different data concerning a depth of the subsoil assumed to be stiff and those concerning the course of groundwater lowering. The set of such bench marks is suggested to be called ad identifying base.

At initially assumed values A', B, α, the values S and correction factors K = P/S are calculated. A dependence of these factors on the time of measurement is approximated by the straight line.

$$K \approx Q \cdot t + R \tag{9}$$

Basing on the criterions Q = 0 and R = 1, the functions $\alpha(A')$ and $B(A')$ can be determined for each bench mark of the base.

The functions obtained are presented in diagrams from where, by evaluating the importance of base points depending on likelihood and accuracy of data and advance rate of subsidence process as well, the best values A', B, are determined which characterize the area under consideration.

Let's take the use of such a technique in the Northern region as example.

As identifying base, the bench marks have been accepted to be numbered with 1868 and 1862. A greater weight is to be attached to the first of them because a distinct reduction of increase in subsidences is observed as the water table approaches to the Mesozoic bedrock.

It was found that subsidences measured in the first years are clearly distinctive from the model (fig. 5). A supposition can be made that it is an effect of other processes than consolidation, e.g. internal suffosion associated with high hydraulic gradients in the loose material. For this reason, two first years were neglected when approximating as per (9).

The fuctions obtained are shown in fig. 6. The correlation coefficients corresponding to the particular points in the diagram are given, and selected values A', B, as well.

In fig. 7, correlations S, P are presented for all bench marks in the region which statisfy minimum criterions of data reliability. The result can be considered as quite satisfactory. High correlation coefficients S,P for points of the base allow to suppose that the model-analogue under consideration is a sufficiently acurate representation of the process of land subsidence in consequence of dewatering, and it may be used as prediction model.

Moreover, the important deviations of P from S at some points can be a basis for hypotheses concerning their causes. One can suppose that there are locally considerable deviations from a characteristic lithological profile or soil properties, or anomalies in dewatering become apparent. So, the observations of subsidences can indirectly prove favourable for the control of geological exploration and dewatering process.

CONCLUSIONS

The investigation of land subsidences produced by dewatering of surface mines is restricted by the scope of measurements carried out at mines for practical purposes of mining operations.

The studies presented have shown that with such constraints simplified models-analogues are better to describe the whole process than a model basing on the principles of soil mechanics but provided that the analogues will function according to the general trends included in these principles and that identification of model parameters will be made in the regions characterized by definite types of geological structure. The models determined in such a manner ensure a high correlation between measured subsidences and those calculated from the model, and they may be used as prognostic models.

It is allowable to suppose that these models can be suitable for an indirect control of drainage and for the control of a correct geological exploration.

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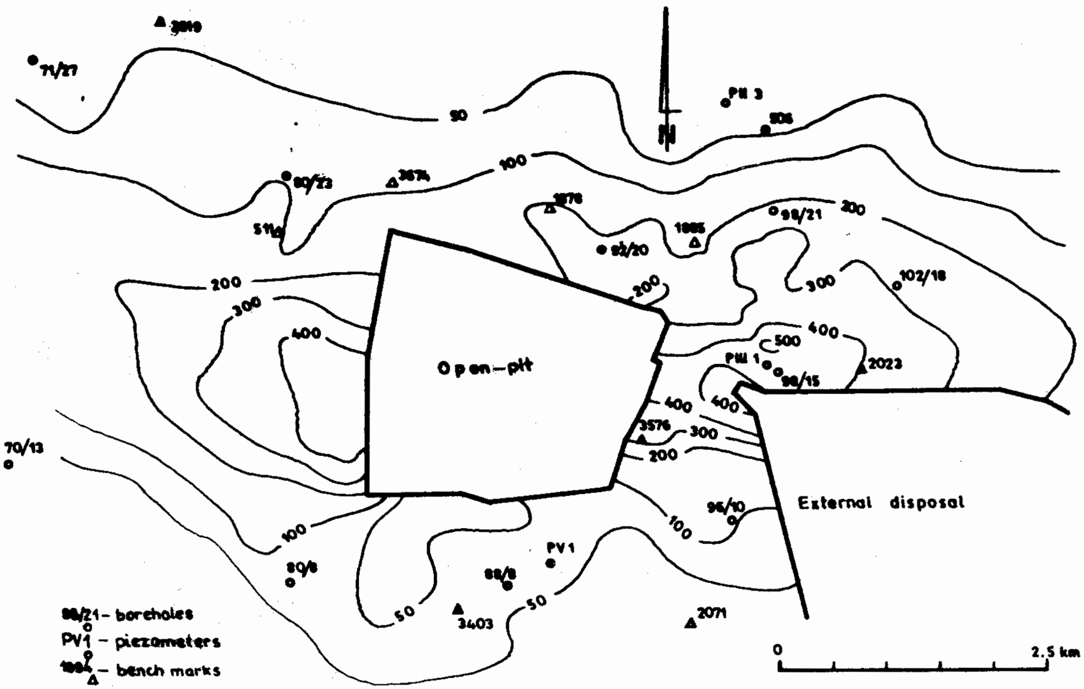

Fig. 1. Land subsidence in the Bełchatów open-pit neighbourhood after eight years of drainage.

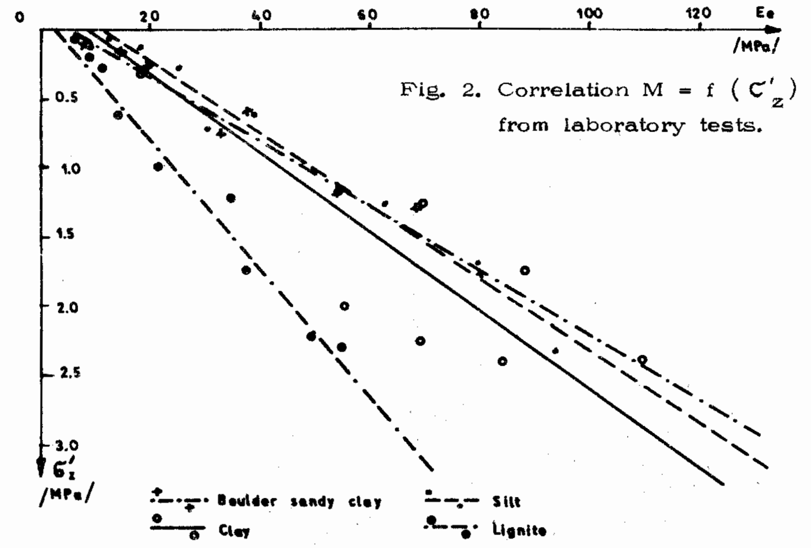

Fig. 2. Correlation M = f (σ'_z) from laboratory tests.

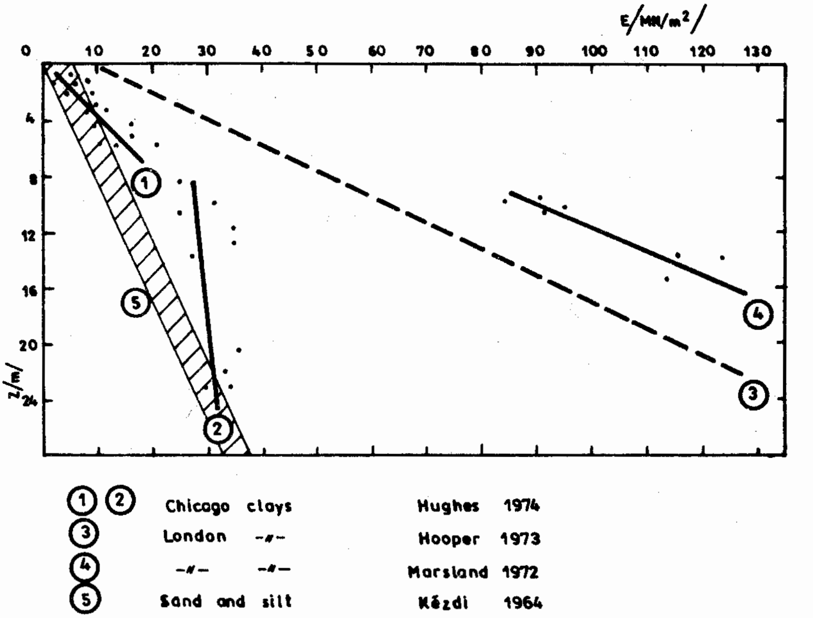

Fig. 3. Correlation M = f (z) from field tests.

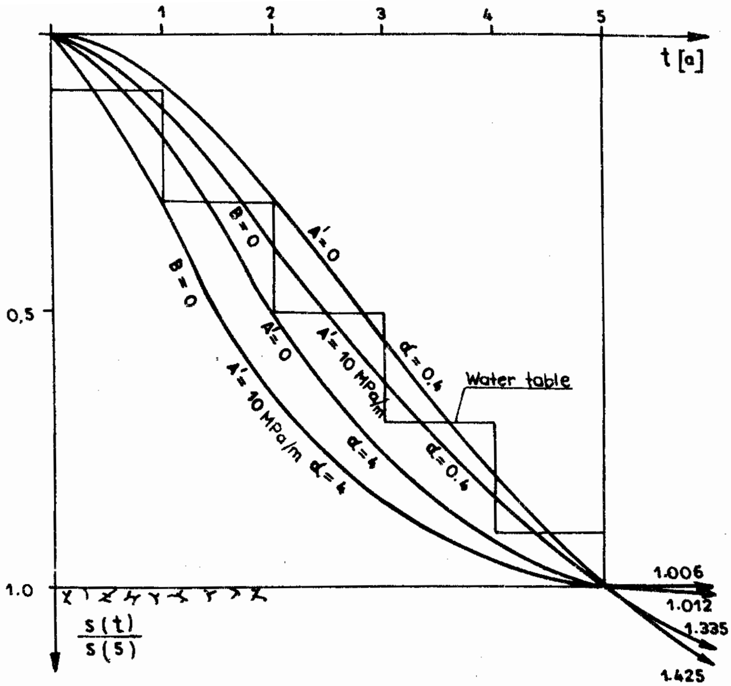

Fig. 4. Influence of A' and on the shape of line
$S(t) / S(5) = f(t)$.

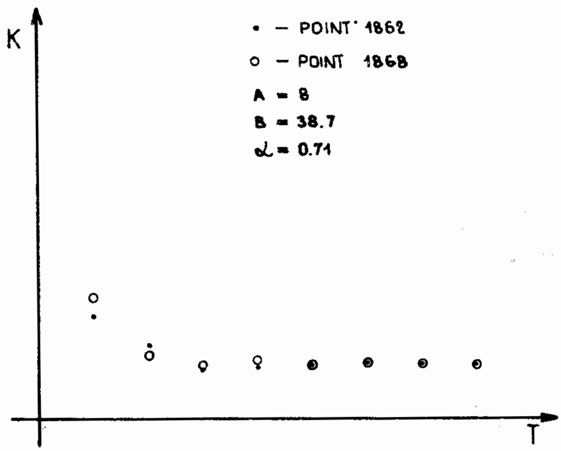

Fig. 5. Irregularities of subsidences in the first years of drainage.

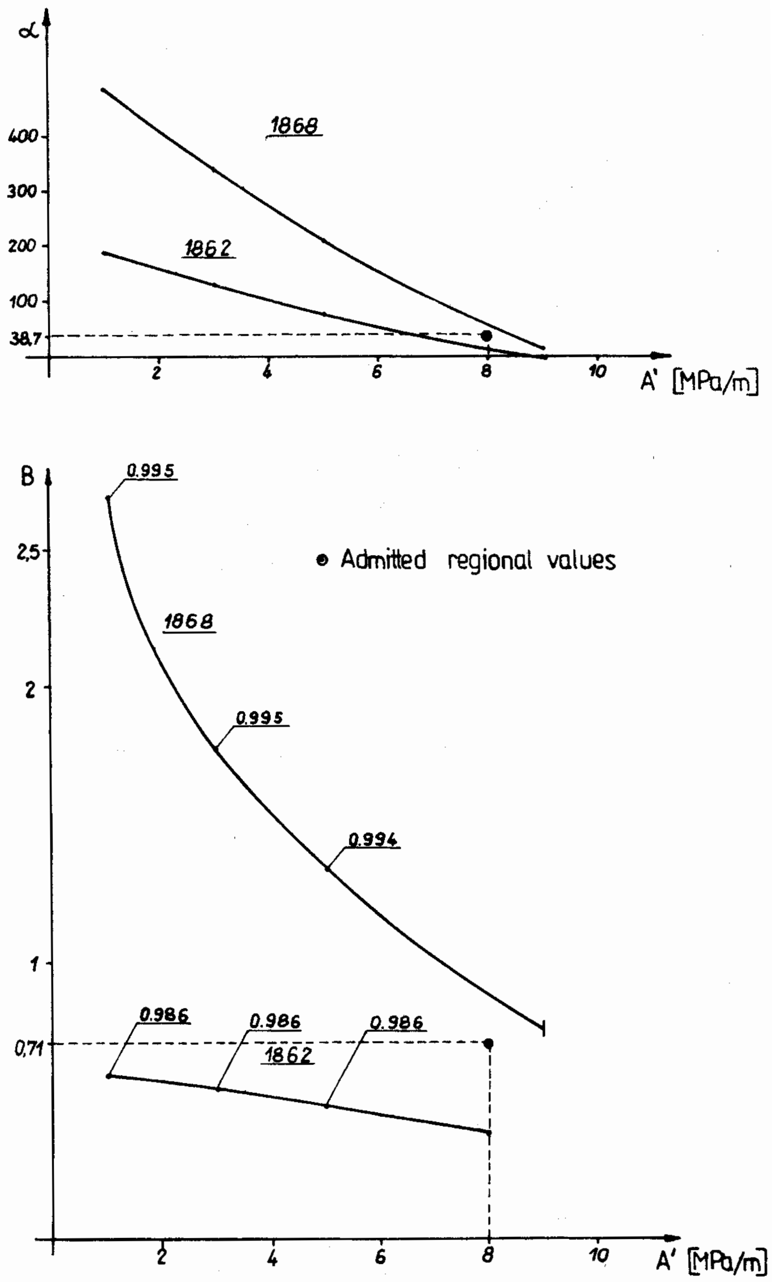

Fig. 6. Relationship (A') and B (A') if Q=0
and R = 1.

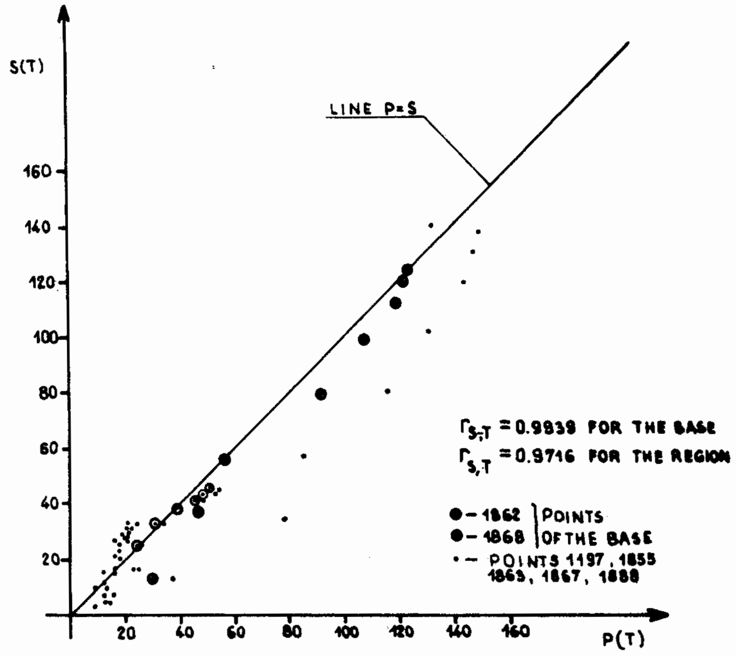

Fig. 7. Correlation of P, S in the Northern region.