Accepted version for publication (post print)
The original or published publication is available at
http://www.springerlink.com/content/qyfefty8qy6gq8pc/

Reference to be cited: *Polemio, M., and Romanazzi, L.: Numerical simulation of groundwater protection works against industrial waste dump, Bull. Eng. Geol. Environ., 57, 253-261, 10.1007/s100640050042, 1999.*

NUMERICAL SIMULATION OF GROUND WATER PROTECTION WORKS AGAINST INDUSTRIAL WASTE DUMP

SIMULATION NUMERIQUE D'OUVRAGES DE PROTECTION DES EAUX SOUTERRAINES CONTRE TOUTE POLLUTION CAUSEE PAR UN TERRAIN DE DECHARGE DE DECHETS INDUSTRIELS

POLEMIO M.
C.N.R. - CE.RI.S.T., Bari (Italy)

ROMANAZZI L.
Istituto di Geologia Applicata e Geotecnica, Facoltà di Ingegneria, Politecnico, Bari (Italy)

Abstract

The use of a deserted clay quarry to collect iron manufacturing-derived special wastes has been carefully assessed with a view to protecting ground water resources.

The shallower ground water is of low quantity and poor quality. It is encompassed by a calcarenites aquifer, the bottom of which consists of clays. A limited calcarenite layer is found below, transgressively lying over the main Apulian carbonate shelf.

The aquifer carbonate rocks enclose a large ground water resource which ultimately flow into the Ionian Sea.

A plastic waterproof diaphragm inert to percolation products has been set up to protect ground water against pollution hazards resulting from the disposal of industrial wastes. The dump is actually located in the vicinity of major industrial plants, the basement of which corresponds to the shallow aquifer.

Both the above basement and the railway cuttings greatly affect the ground water flow. Therefore, hydrogeological applied numerical calculation techniques have been resorted to. The aim was to evaluate the impact of a drainage trench on the ground water flow along with any noticeable influence of the latter on construction works and industrial plants in place.

Résumé

L'utilisation d'une carrière d'argile comme terrain de décharge de déchets sidérurgiques a été soigneusement évaluée en vue de sauvegarder les ressources en eaux souterraines.

La main d'eau moins profonde est de mauvaise qualité. Elle est renfermée dans un aquifère en calcarénite dont le lit est constitué par des argiles faisant l'objet d'une exploitation intense; au-dessous, une couche de calcarénite sous-jacente traverse la plateforme carbonatée des Pouilles. Les roches carbonatées de l'aquifère renferment une nappe qui s'écoule jusqu'à la Mer Ionienne.

Un diaphragme étanche à l'eau et inerte aux produits de percolation a été réalisé pour protéger les eaux souterraines contre les risques de pollution par les déchets industriels de la décharge. Le dispositif a été conçu suite à une évaluation soignée des impacts sur la circulation

d'eau souterraine. Le terrain de décharge est situé près d'établissements dont le sous-sol correspond à la nappe peu profonde.

Le sous-sol et les tranchées ferroviaires influent grandement sur la circulation de l'eau souterraine. D'où le recours à des techniques de calcule numérique appliqué à l'hydrogéologie. Le but étant d'estimer l'impact du diaphragme sur la circulation d'eau souterraine ainsi que toute influence de celle-ci sur les ouvrages existants.

1. Introduction

The landfill site proposed for the storage of toxic and other wastes released by the Iron Manufacturing Plant in Taranto (southern Italy) is an abandoned clay pit with an area of approximately 75,000 m^2 and a total capacity of 1.2 x 10^6 m^3 (Fig. 1). Before it could be made operational however, some ground protection works were required.

An impermeable diaphragm was installed with a view to preventing seepage from the adjacent shallow ground water (Spilotro 1983). The construction of the plastic diaphragm alone would result in the ground water rising and hence adverse affect the basement equipment in a nearby plant. It was considered necessary therefore to investigate the piezometric variations and what additional action, if any, was necessary to protect the facilities (Polemio and Romanazzi 1991). The studies carried out, supported by numerical modelling of the ground water flow, led to the design of a drainage trench.

2. Climatic, geological and hydrogeological setting

The area investigated is approximately 2.5 km from the Ionian coast, in the vicinity of the picturesque Gulf of Taranto where one of the most important iron manufacturing plants is situated (Fig. 2).

The mean annual rainfall recorded over a period of 70 years is 468 mm; the minimum values being reported in the Salentine peninsula, south-eastern Italy. The mean annual temperature, based on records over 58 years, is high in the area, 17 °C, as is frequent along the north-eastern Ionian coastline.

The mean hydrological balance was derived using the Thornthwaite-Mather approach (1957). Assuming a specific retention of 100 mm, there would be an 82 mm mean annual "water surplus" (infiltration plus runoff), of which 70 mm would seep into the subsoil, thus feeding the aquifer. According to the Thornthwaite classification, the climate is semi-dry and the water surplus is in the range from limited to null.

In the area investigated, the oldest deposit is a Cretaceous calcareous formation commonly referred to as the Limestones of Altamura. Transgressively overlying these are the Calcarenites of Gravina. Above both of these are the marly clays known as the Subappennine clays in which Hyalinaea Balthic is found (Ciaranfi et al. 1971, Cotecchia et al. 1977, Dell'Anna and Garavelli 1972).

During the post-Calabrian and early Holocene period the Subapennine clays were eroded by the sea to form platforms above which calcarenite and sandy deposits transgressively accumulated forming coastal terraces sloping towards the present shoreline (Ricchetti 1970). There is little coastal topography, except the gently incised stream systems. The result of geological, hydrogeological and geotechnical surveys are summarised in Figs. 3 to 6. The diagram showing natural radioactivity (Fig. 3) highlights the nature of the sandy and calcarenite soils overlying the clays while Fig. 4 provides the parameters of the clays and slightly sandy soils. The laboratory analyses indicate the average values of dry unit weight and water content to be 1600 kg/m^3 and 27% respectively although the unit weight is as low as 1300 kg/m^3 at 6 m above sea level. The liquid limit is generally 66 to 70% and occasionally exceeds 80% while the activity is close to unity. Undrained shear strength varies between 1.8 and 5 kg/cm^2, generally exceed 3.5 kg/cm^2 at depths greater than 4 m below sea level.

Seven Lefranc water intake tests were undertaken (SN1, SN2, SN3, SN4, S16, S21 and S18 borehole, Fig. 10). Intake length varied from 0.8 to 3.3 m, depth of intake top varied from 3 to 5.5 m and water table depth varied from 3.3 to 5.8 m. The water table was under the top intake level in same borehole as low saturated aquifer thickness. The intakes were realised in calcarenite and sandy levels of shallow aquifer. The tests indicated minimum, mean and maximum permeabilities of 2×10^{-7}, 1×10^{-5} and 3×10^{-5} m/s respectively. In the calcarenites the hydraulic conductivity decreased with depth due to the progressive increase in the pelitic content of the material while the underlying clay had a permeability of 10^{-7} m/s.

The average depth of the shallow calcarenite and sandy aquifer bottom (Polemio 1996) is 5.6 m; the average water table was 3 m below ground level.. A deep aquifer is also present consisting mainly of limestones. This extends outwards under the sea such that in addition to surface springs, submarine springs also occur. The lower ground water is kept under pressure by the overlying Subapennine clays which form an effectively impermeable bed beneath the generally calcarenitic and sandy shallow aquifer (Figs. 2 and 5). There is about a 60 m tick clay formation between shallow aquifer bottom and deep aquifer top in the site (Fig. 5).

3. Ground water quality and aquifer vulnerability

The landfill site is an abandoned clay pit. Overlying grey-blue clays there is an horizon of calcarenite through which the shallow ground waters flow towards the quarry (Fig. 7). Chemical analyses carried out on samples from the shallow ground water highlighted the occurrence of pollutants: arsenic, iron and manganese. The presence of arsenic, iron and manganese together with the its high salinity (10-15 g/l) means the water cannot be used for industrial or civil activities. In contrast, the water from the carbonate aquifer exhibits excellent chemical properties and must therefore be protected.

With regard to the relationship between the ground water and the pollution hazards, it should be noted that underground water exchanges along the vertical axis may occur at the level of :

- the deep ground water (3 m asl);
- the shallow ground water (12 m above sea level);
- the former clay pit and present landfill (-11 m, which was previously masked by a freely flowing "main d'eau" at 0.2 m asl).

It was therefore appreciated that under these conditions, limited direct flows from both aquifers towards the quarry depression were likely to occur. These flows were estimated as 170 m^3/day from the shallow water table and 0.2 m^3/day from the deep water level, which was not subject to rapid recharge from the bottom of the clay pit. Once the landfill was operational, however, the progressive filling would assist the percolation of chemical products into the ground water. The presence of the shallow aquifer in particular was liable to result in pollutants being diffused and possibly reaching the deep aquifer, compromising the quality of water outflowing close to springs.

4. Actions to protect ground water

For the landfill to be reliable, it would be important to prevent any leakage from either the dump itself, through the surrounding clay cover soil or as a result of seepage from the shallow aquifer. As a result, a ring-shaped plastic diaphragm was designed to extend from the surface, through the shallow permeable layers, to the clays. A cement bentonite vertical trench was designed and realised. The 0,50 m thick plastic cut-off wall is anchored for a depth of 1 m into the basal clays and extends around the entire 1150 m perimeter of the old quarry, thus forming a cylinder with a closed generatrix. In all points the longitudinal section of this curtain follows the surface profile of the top of the impermeable grey-blue clay formation, the position of which was determined in situ by sinking numerous exploratory geological boreholes (Fig. 6).

The plastic cut-off wall is formed of 3,20 m panels. The secondary panels were placed after installation of the primary units, interpenetrating for a distance of 0,50 m on both sides. Interpenetration of the secondary and primary panels was achieved at the moment when the cement-bentonite-water mix to be removed had a soft-plastic consistency. All trenching was performed by means of a cabled self-guiding hydraulic bucket excavator.

Owing to the loose/semi-stony nature of the ground above the clays, which lie some 5 to 9 m below ground level, thewalls of the trench had to be temporarily stabilized by the use of special biodegradable muds during excavation.

The efficiency of the plastic diaphragm was monitored by 14 open micro-piezometers inserted within the diaphragm together with 29 internal and external piezometers. The piezometric monitoring commenced before the construction of the impermeable diaphragm in 1984 and continued until 1992 with more than 100 measuring cycles of the shallow ground water undertaken over a period of five years. The monitoring continued after the execution of the diaphragm in order to check whether the assumed piezometric increase in the shallow water table - resulting from the construction of the diaphragm - might affect the nearby basement plants, located about 6 m above the ground level. It was assumed that there would be a piezometric increase in the shallow water table as a result of the construction of the diaphragm and hence it was considered prudent to check whether this was affecting the basements. As seen in Fig. 9, the plastic diaphragm clearly created an artificially high ground water level which could severely affect the basements of the industrial works.

The most practical solution consisted of a gravity flow drain trench taking ground water towards a railway cutting adjacent to the landfill site.

5. Numerical simulations

The drain trench was designed to be installed upward the diaphragm and perpendicular to the shallow ground water path, in order to prevent any excessive piezometric increases resulting from the construction of the diaphragm itself. A hydrogeologically applied numerical calculation approach was adopted, but this proved extremely difficult to apply in view of:

1. the limited thickness of the permeable soil encompassing the shallow water table at 6 m;
2. the piezometric height of the water table, only 2-3 m above the impermeable clay;
3. the presence of basement facilities, railway cuttings and holes in the vicinity which affected the flow pattern.

As a consequence, numerous calibrations and adjustments were required to take account of both these factors and the available piezometric and rainfall data.

5.1 Background of the three-dimensional numerical flow model

Ignoring the effects of fluid density variations, the three-dimensional aspects of the underground flow can be described by the following differential equation:

$$\partial\left(\frac{Kx\cdot\partial h/\partial x}{\partial x}\right)+\partial\left(\frac{Ky\cdot\partial h/\partial y}{\partial y}\right)+\partial\left(\frac{Kz\cdot\partial h/\partial z}{\partial z}\right)-W=Ss\cdot\frac{\partial h}{\partial t} \qquad [1]$$

where Kx, Ky and Kz are hydraulic conductivity coefficients of the medium along x, y and z axes, parallel to the major flows h is the potentiometric head W is the inlet/outlet flow per volume unit Ss is the specific storage coefficient of the aquifer and t is time

Equation 1 describes the ground water flow under transient conditions in a heterogeneous and anisotropic aquifer. Given the initial boundary conditions, the equation may be regarded as a mathematical read out of ground water flow. The approach is based on the finite difference method (Mcdonald and Harbaugh 1988).

The modelling of the drain trench assumed construction to be in a continuous phreatic aquifer some 600 to 800 m wide and no more than 10 m deep, which could be varied from cell to cell to take account of the known stratigraphy. It was broadened upstream sufficiently to prevent any impact on the simulation results. The layer underlying the aquifer was assumed to be impermeable.

The effects of the construction of the drain trench were investigated by means of a grid of 870 elements or cells (Fig. 10). The post-calibration value of hydraulic conductivity of the calcarenite bank was found to be 10^{-5} m/s.

As this was consistent with the measurements taken, three numerical models were defined to illustrate three different ground water circulation conditions.

Case I

The first case served to calibrate the model under steady state. For this, the hydrological data pertaining to the monitoring period prior to the execution of the work were used.

The calculation grid covered an area characterised by ancient man-made incisions and industrial plants. The incisions enable the "natural" flow from the shallow aquifer to reach the quarry as well as the eastern end of the investigated area.

In order to simulate these conditions, two scenarios were envisaged. The absence of the aquifer was simulated by introducing non-active cells while the presence of drainage points to the quarry and the railway cuttings were taken into account by the boundary conditions of the assigned piezometric load.

During the first stage, monitoring-derived loads were assigned to the upstream side boundary. Cell hydraulic conductivity was calibrated and the upstream model input discharge calculated. A flow rate was then assigned to the upstream boundary cells and the water levels in the aquifer allowed to fluctuate.

Figure 11 shows the numerically defined lines reported before the quarry was used as a landfill. The circulating flow rate measured under steady state was found to be 1 l/s - a low value ascribable to the poor hydrogeological characteristics of the aquifer.

In order to obtain objective data for the evaluation of path flow lines and distance over time, a sub-model was designed using the Path3d code (Zheng, Bradbury and Anderson 1989). Ten marker particles, which would move with the water, were injected into the shallow aquifer at ten different sites.

All of the particles reached the 6 - 23 (row - column) cell along the quarry boundary. The estimated travel time from the boundary to the final destination in the area of artificial draw down was approximately three years (Fig. 12). The flow rate did not exceed 10^{-6} m/s. This simulation highlighted both stream lines and time, the latter being fundamental to the vulnerability of the phreatic aquifer with almost no water logging at all below potentially polluting industrial plants. It also enabled an assessment to be made as to whether the combination of an impermeable diaphragm and a drain trench would increase the vulnerability of the aquifer compared to its state before the landfill site was put into operation.

Case II

In the second study, the model assumed the implementation of the drainage trench and impermeable diaphragm under steady state conditions. The impermeable diaphragm suppressed the draining effect of the man-made incisions. For the purposes of the calculations, this was accommodated in the diaphragm layout by the use of 40 cells (Figs. 10 and 13). The increase in hydraulic conductivity (K) along the drainage trench was included as a function of the replacement of the in situ soil (K_1) with coarse-grained material (K_2). The value of soil was replaced by an arbitrary value of K*

$$K^* = b_1 \cdot K_1 + b_2 \cdot K_2 \,; \qquad \text{con } b = b_l + b_2 \qquad [2]$$

where b is the overall width of the cell b_1 is the portion with the original soil in place b_2 is the width of the drainage diaphragm = 0.6 m. K* was found to range between 1.6 and 12 K_1. These values, once logged into the model, showed that under steady state conditions the installations would permit the drainage of l l/s.

Figure 14 shows that the drainage trench would be successful as the difference between the piezometric heights in Case I and Case II does not exceed 0.6 m in absolute values.

Travel time and velocity did not differ significantly from those calculated for Case 1, being +/- 5%. It was therefore considered that the trench-induced average increase in hydraulic conductivity corresponded to increased pathways and hence the drainage work would not increase the vulnerability of the aquifer.

Case III

Based on Case II, a further study was undertaken to clarify the impact of unusual meteoric phenomena by simulating the effect of exceptional recharge of the ground water. A peak monthly rainfall value of 290 mm over 30 days was assumed with a similar direct recharge intensity which remained constant during 30 consecutive days. Calculations were made on the basis of exceptional rainfall (from 70-year records), a slow natural filtration rate and the low capacity of the unsaturated aquifer. No account was taken of evapotranspiration or run-off losses and an effective porosity of 0.15 was assumed.

Figure 15 shows the rise in the ground water level after 30 days of simulation, which was considered to be consistent with the protection of the basement facilities in the vicinity of the landfill site. The simulation also indicated a drained flow rate of 3-4 l/s which it was considered could be regarded as the maximum flow which would pass along the drainage trench in the case of exceptional flooding. This was consistent with the hydraulic potential of the ultimate recipients of the drainage trench, the free-flowing conduit discharging into the railway cutting.

6. Conclusions

Due to the presence of shallow and deep-seated groundwater and the problem posed by the proximity of industrial establishments whose foundations are at or below the bed of the shallow aquifer, the creation of a toxic waste disposal facility in the abandoned quarry could have involved a high hydrogeological risk.

However, construction of a ring-shaped impermeable plastic cut-off wall or diaphragm ensures here will be no leakage from the landfill site towards groundwater nor from the latter towards the former. The efficiency of the cut-off wall has been checked by prolonged monitoring via piezometers installed both inside and outside the site, together with micropiezometers completed in the cut-off itself.

Provision is also made for a drainage trench to minimize the effects of the cut-off on groundwater movement, especially the possibility of piezometric build-up near industrial buildings. The functionality of this trench has been simulated by mathematical models which have also been adopted to verify that the group of works concerned ensures an adequate level of protection for local groundwater resources.

REFERENCES

CIARANFI N., NUOVO G., RICCHETTI G.,1971. Le argille di Taranto e di Montemesola (studio geologico,geochimico e paleontologico). Boll.Soc.Geol.Ital.,vol.90,Roma.

COTECCHIA V., MELIDORO G., ROMANAZZI L., SPILOTRO G. ,1977. Osservazioni sul comportamento geotecnico delle argille di Taranto determinato da alcuni caratteri geologici. Atti II Congr.Naz.Argille dell'A.I.P.E.A.

DELL'ANNA L., GARAVELLI C.L.,1972. Notizie mineralogiche e chimiche su sedimenti attuali del Golfo di Taranto. Geol.Appl. e Idrogeol.vol. VII, Bari.

POLEMIO M.,1996. Le calamità idrogeologiche dell'inverno 1995-96 nel territorio tarantino. Conv. Int. "La prevenzione delle catastrofi idrogeologiche : il contributo della ricerca scientifica", CNR IRPI, Alba 5-7 Novembre 1996.

POLEMIO M., ROMANAZZI L.,1991. Vulnerabilità e protezione delle acque sotterranee dal rischio di inquinamento derivante da una discarica controllata per rifiuti speciali (area industriale di Taranto). Pubbl. GNDCI n. 559, Biennal Conference ANDIS, 61-72, Roma.

Mc DONALD M.G., HARBAUGH A.W.,1988. A modular three-dimensional finite difference groundwater flow model. USGS.

RICCHETTI G.,1970. Nuove osservazioni sui depositi plio-pleistocenici nei dintorni di Taranto: I "tufi" calcarei con "Artica Islandica", Boll.Soc.Geol.Ital., vol.89.

SPILOTRO G. ,1983. Studio geologico,geotecnico ed idrogeologico di un'area di cava in argille al fine della valutazione dell'idoneità all'uso come recipiente di scarichi industriali, Geol.Appl. e Idrogeol, vol.18, Bari.

THORNTHWAITE, C.W. & MATHER, J.R. (1957). Instructions and tables for computing potential evapotraspiration and the water balance. Drexel Inst. of limat., 10, 323 pp., Centerton.

ZHENG C., BRADBURY K.R., ANDERSON M.P.,1989. A computer model for calculating groundwater paths and travel times in transient three-dimensional flow fields. Information Circular, Wisconsin Geological and Natural History Survey, Madison, Wisconsin.

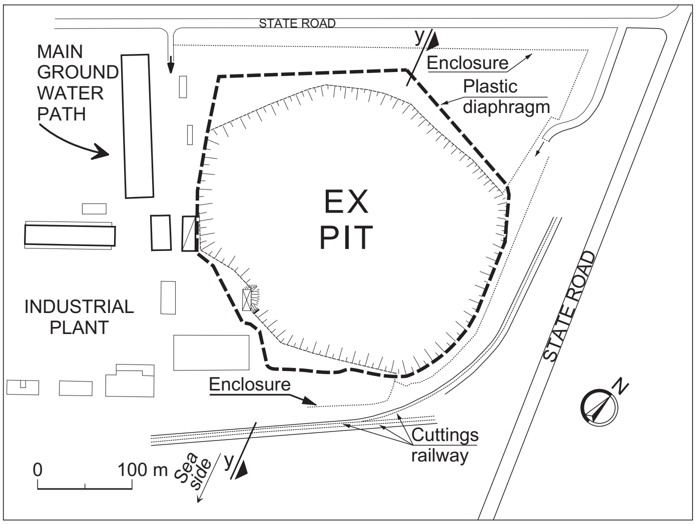

FIG. 1 - Plan of the pit area.

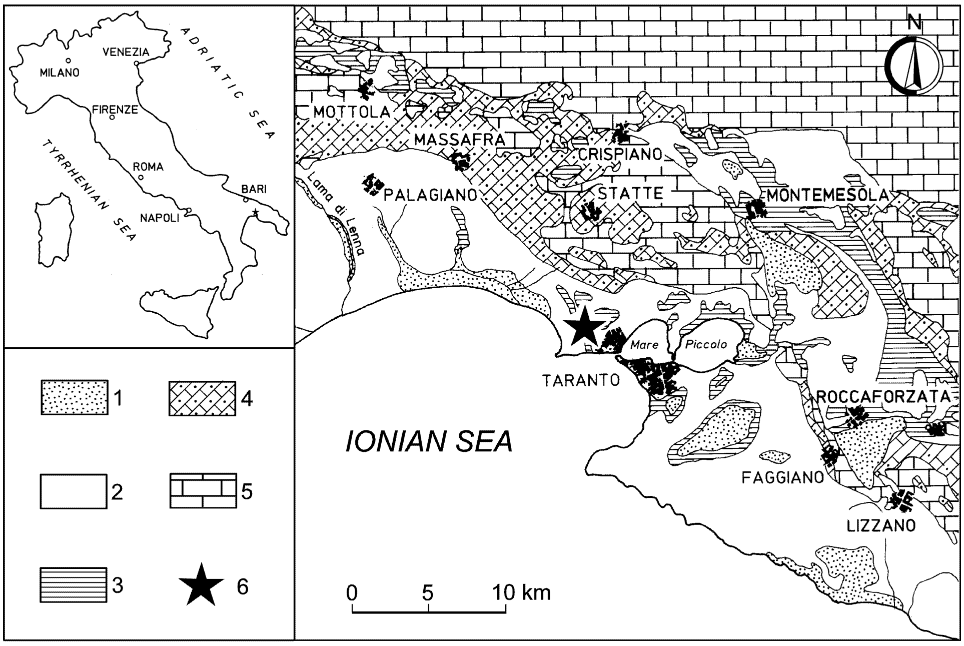

FIG. 2 - Schematic geological map. 1) Alluvial deposits; 2) marine terraced deposits; 3) Subappennine clays; 4) Gravina calcarenite; 5) Altamura limestone; 6) wast dump.

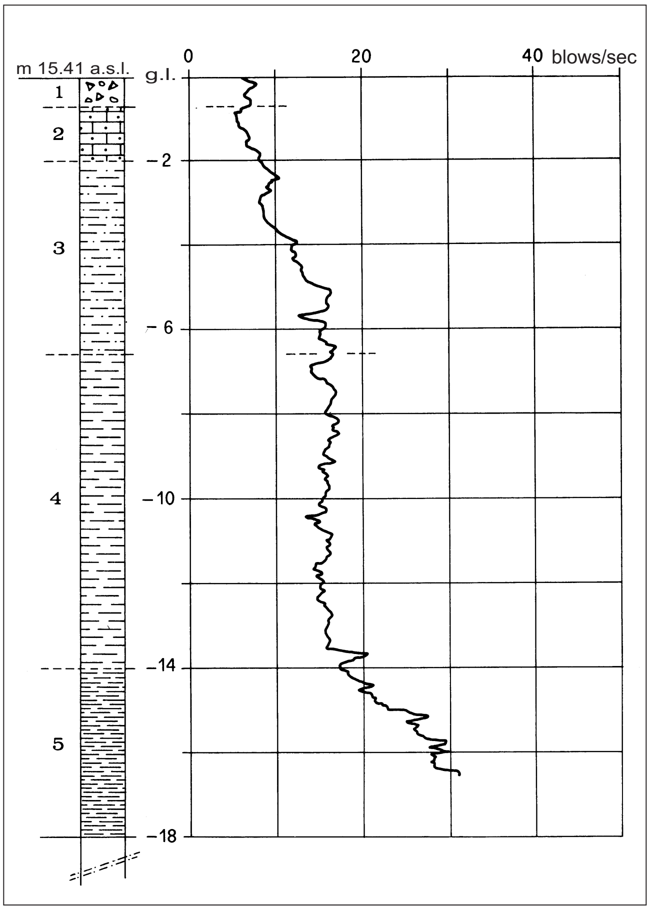

FIG. 3 - γlog profile. 1) fill; 2) calcarenite; 3) sandy clay; 4) blue clay; 5) green marly clay.

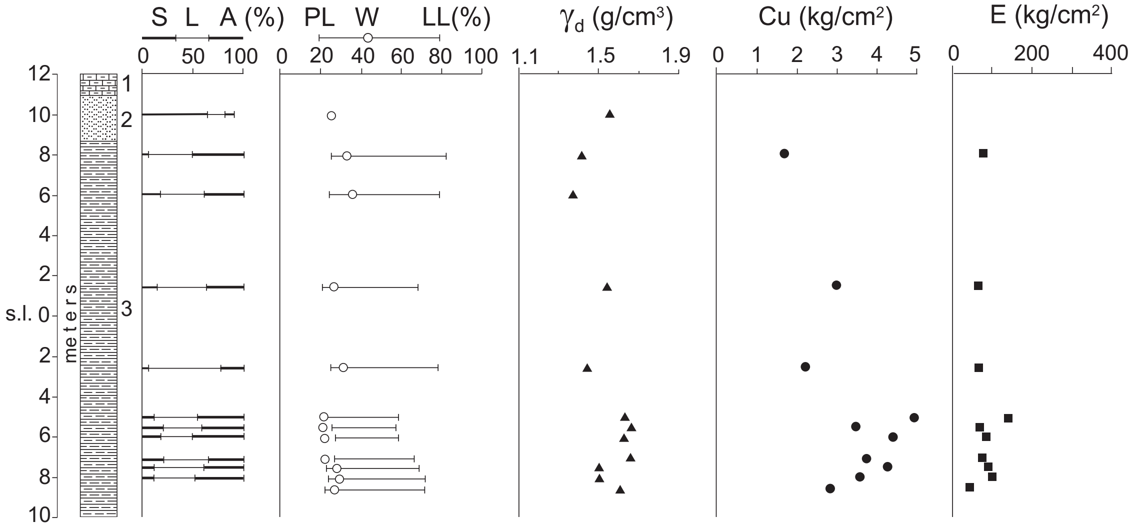

FIG. 4 - Typical geotechnical profile from area examined. 1) calcarenite; 2) sand; 3) blue clay; S= sandy fraction; L= silty fraction; A= clayey fraction; PL= plastic limit; W= natural water content; LL= liquid limit; γd= dry unit weight; Cu= undrained shearing resistance; E= modulus of deformation.

Reference to be cited: Polemio, M., and Romanazzi, L.: Numerical simulation of groundwater protection works against industrial waste dump, Bull. Eng. Geol. Environ., 57, 253-261, 10.1007/s100640050042, 1999.

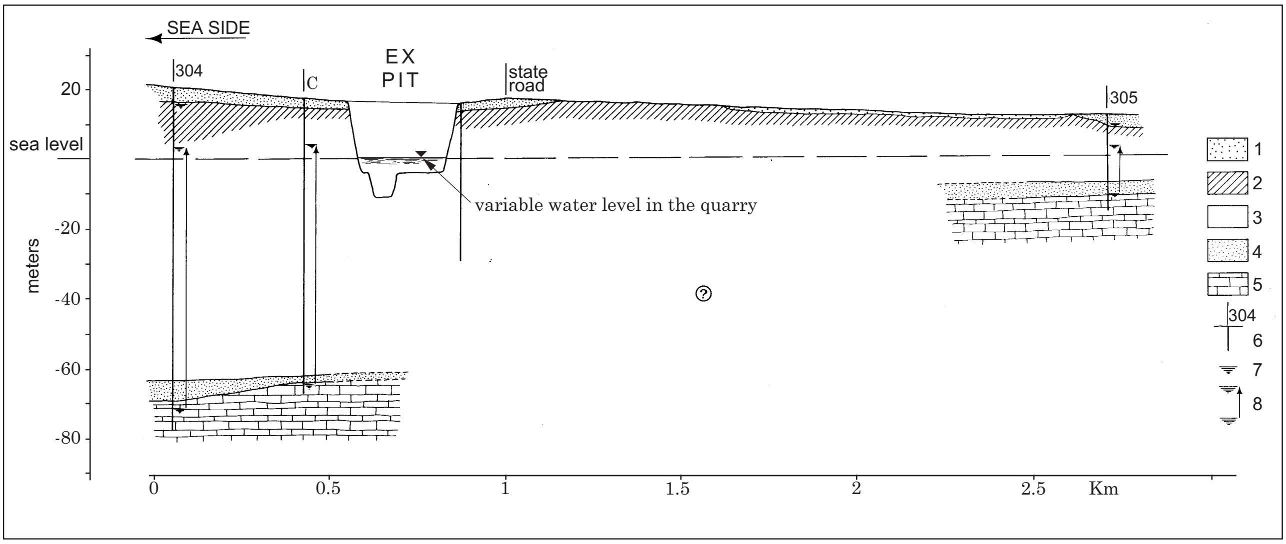

FIG. 5 - Geolithological section. 1) Palustrine deposit; 2) sandy clay; 3) blue clay; 4) calcarenite; 5) limestone; 6)boring or well; 7) shallow gorundwater level; 8) deep ground water level.

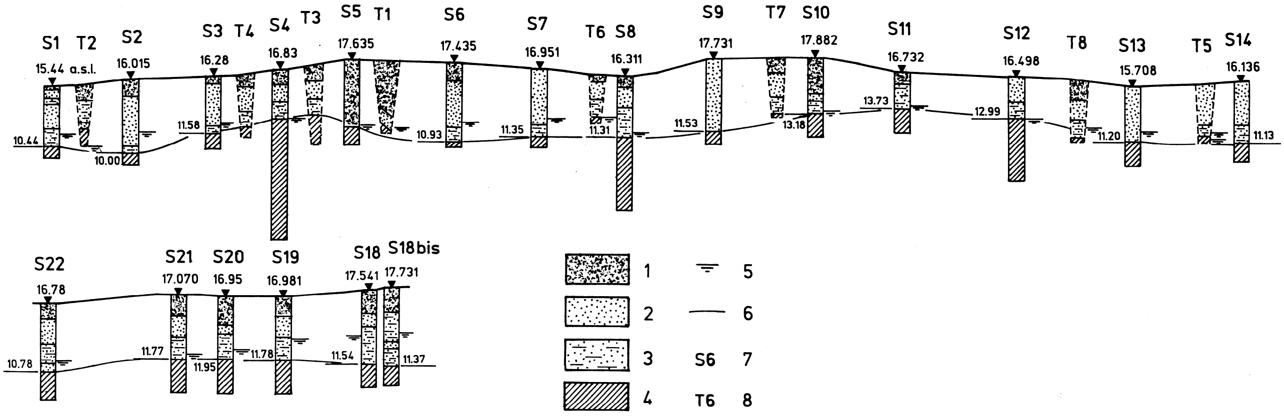

FIG. 6 - Reconstruction of landfill lithostratigraphic perimeter. 1) fill; 2) calcarenite; 3) sandy clay, 4) blue clay; 5) shallow ground water level; 6) top clay surface; 7) borehole; 8) dug well.

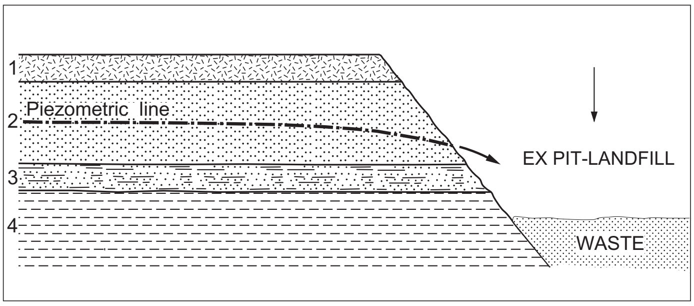

FIG. 7 - Pit schematic section before the landfill realization .1) fill; 2) calcarenite; 3) sandy clay; 4) blue clay.

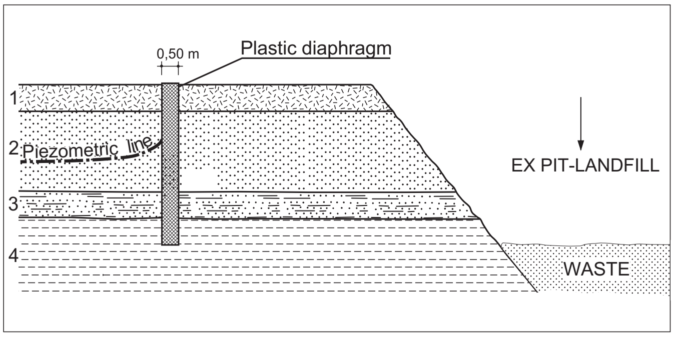

FIG. 8 - Schematic section of the impermeable plastic diaphragm put in the base clay. 1) fill; 2) calcarenite; 3) sandy clay; 4) blue clay.

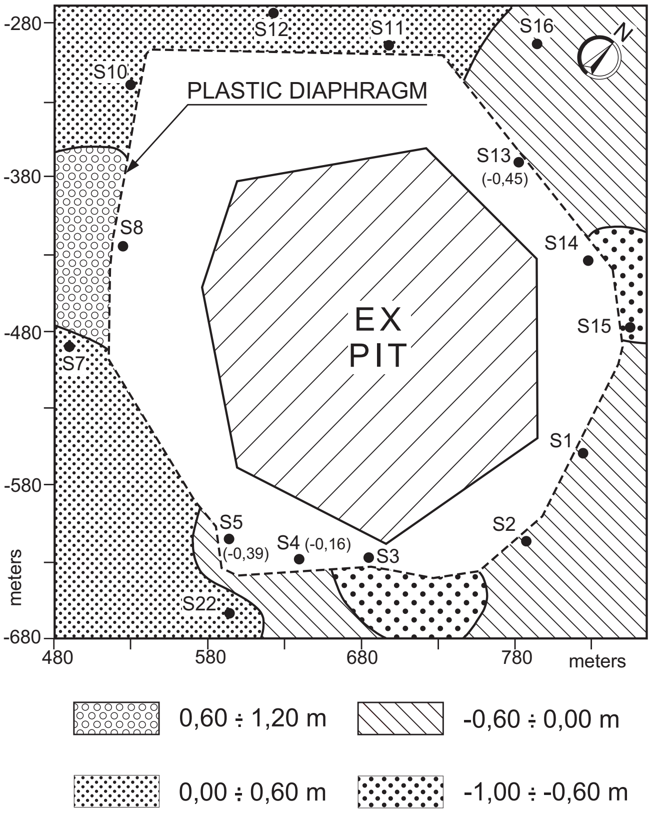

FIG. 9 - Map of maximum piezometric increases occurred over 5 years of observations, following the construction of the impermeable plastic diaphragm. the variations in brackets have occurred within the diaphragm.

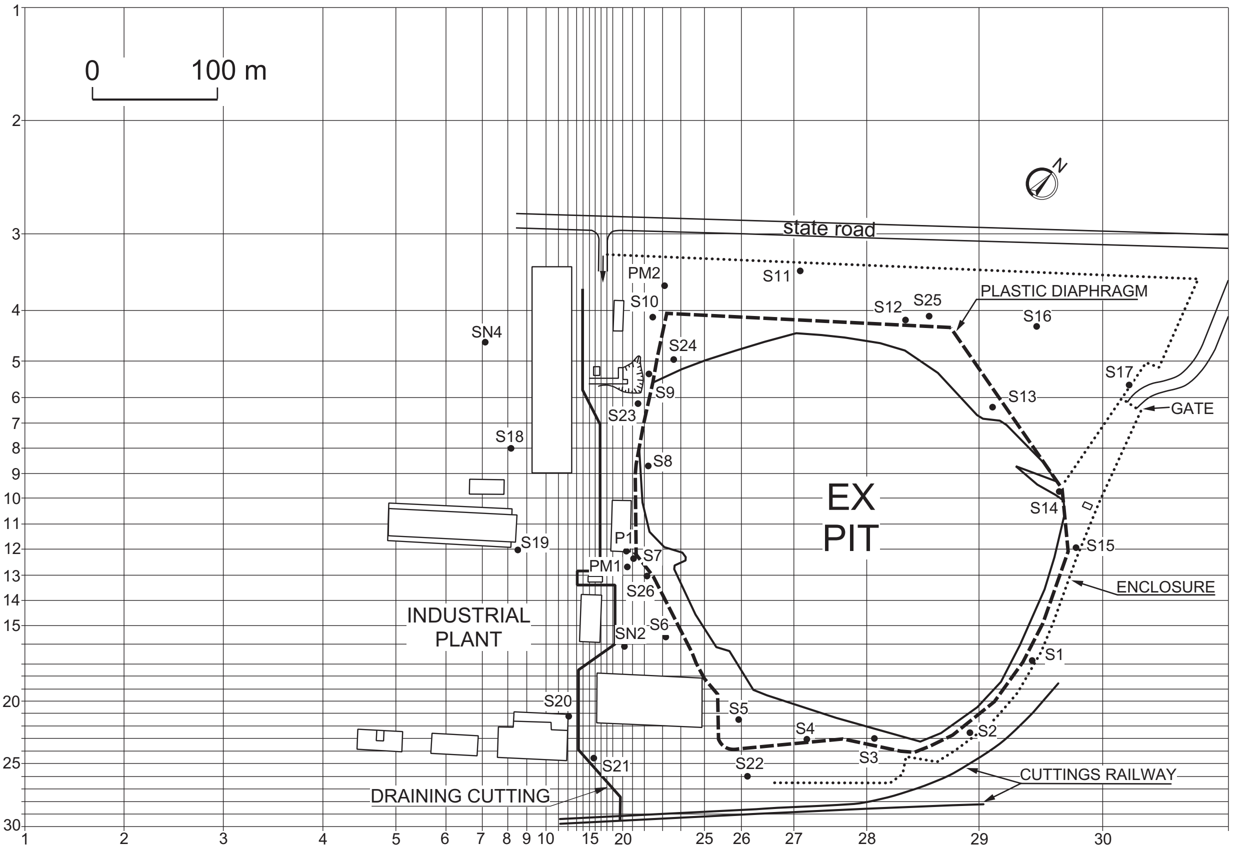

FIG. 10 - Planimetry of the draining trench and hydrogeological numerical calculation grid at finite differences.

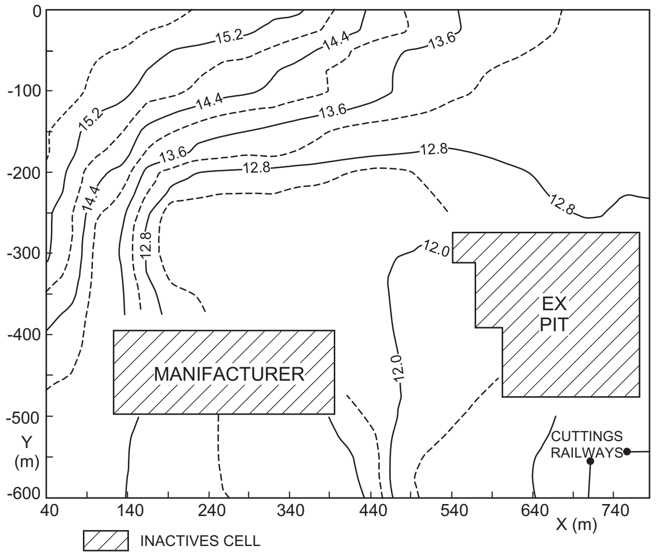

FIG. 11 - Flow steady state; isophreatic lines (m asl) case I, no plastic diaphragm, situation prior to 1984.

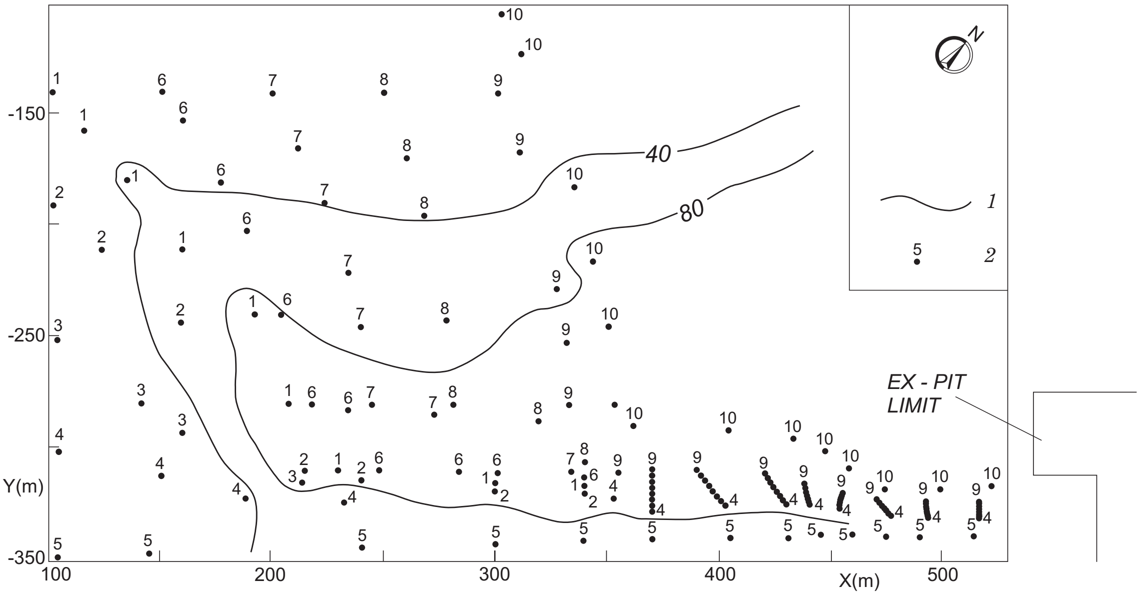

FIG. 12 - Case I. Isochronal lines (10^6 s) defined by 10 marking particles 1) isochronal lines; 2) location of particles.

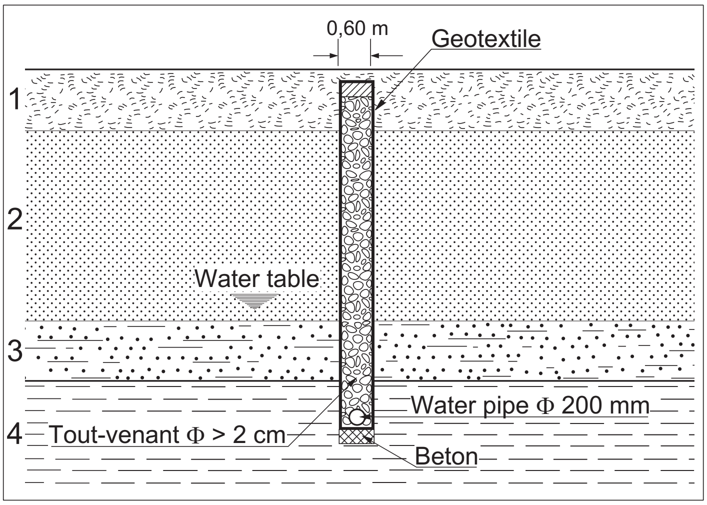

FIG. 13 - Cross-section of the draining trench. 1) Fill, 2) calcarenite, 3) sandy clay, 4) blue clay.

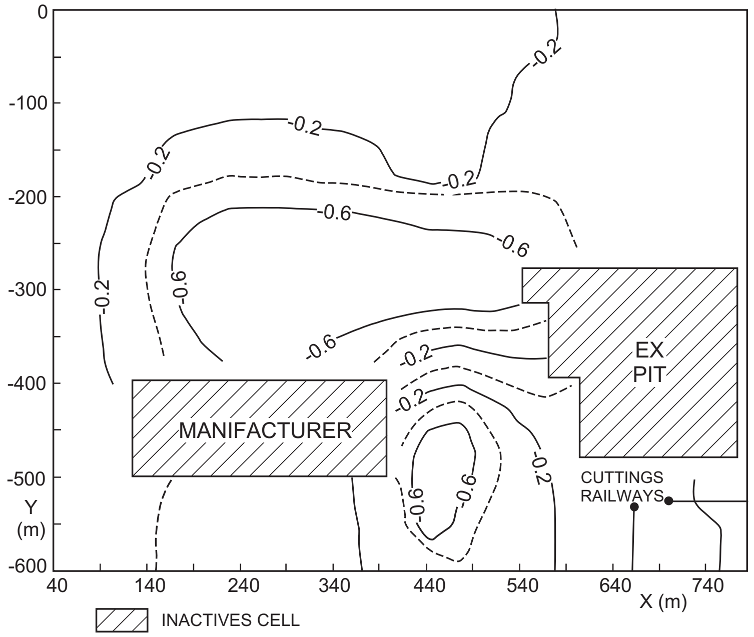

FIG. 14 - Piezometric variations. Lines of equal value (m): case II - case I.

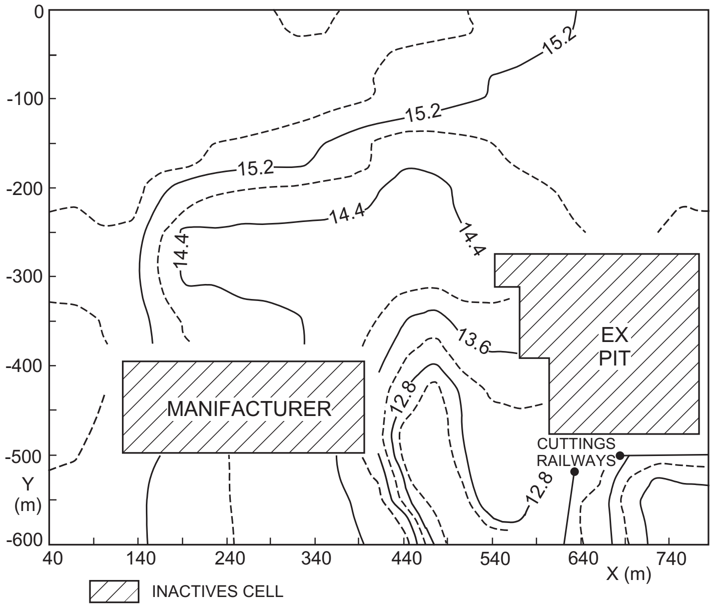

FIG. 15 - Flow steady state after 30 days of simulation, isophreatic lines (m asl): case III exceptional recharge related to the draining trench and the plastic diaphragm.