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THE CEMENT-BENTONITE DIAPHRAGM OF THE MALAGROTTA MUNICIPAL WASTE LANDFILL (ROME, ITALY): EFFICIENCY ANALYSIS

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EXTENDED ABSTRACT

La discarica di Rifiuti Solidi Urbani (RSU) della Città di Roma, una delle più estese d'Europa, nasce nell'area di Malagrotta dove erano presenti, tra gli anni '50 e i primi del 1960, importanti attività di estrazione di sabbia e ghiaia utilizzate come inerti nelle costruzioni, destinate alla rapida espansione urbana della Città di Roma del dopoguerra, ma anche alla realizzazione di importanti infrastrutture come le piste dell'Aeroporto Leonardo da Vinci di Fiumicino (Roma). La complessa stratigrafia dell'area, schematizzata, dall'alto verso il basso, è caratterizzata dalla presenza di depositi vulcanici, sabbie e ghiaie. Questi depositi si trovano al di sopra della importante formazione geologica delle argille grigio-azzurre di età Plio-pleistocenica, ad elevata consistenza e bassa permeabilità (Carboni, 1980). Lo spessore delle argille grigio-azzurre è molto importante e presenta, nell'area di indagine, valori non inferiori ai 100 metri. Il contatto con le soprastanti sabbie e ghiaie è molto irregolare e si sviluppa su una superficie trasgressiva. Lo spessore delle ghiaie, pertanto, varia da pochi metri fino a decine di metri (Galeotti *et alii*, 1990; Carboni, 1980). E' in questo ambiente geologico che lo smaltimento dei Rifiuti Solidi Urbani ha trovato le condizioni ideali, grazie alla presenza di molte cavità, ereditate dall'asporto di grandi quantità di materiali inerti per un volume stimato, nel 1987, in oltre 200×10^6 m^3.

A seguito del Decreto del Presidente della Repubblica (DPR) 915/82 del 10 settembre 1982, emanato in accoglimento di tre Direttive europee, fra le quali la Direttiva 75/442/CEE del Consiglio, del 15 luglio 1975, relativa ai rifiuti, la discarica è stata sottoposta a interventi di bonifica e di messa in sicurezza. L'intervento più importane di adeguamento alle nuove normative, dal punto di vista sia economico sia tecnico-scientifico, è rappresentato dall'isolamento idraulico dell'area destinata a discarica, costituito da un diaframma cemento-bentonite fondato a profondità variabile (Fig. 1, 2, 3) e ammorsato per oltre due metri nelle argille grigio-azzurre sovraconsolidate di base. Le miscele di cemento-bentonite, utilizzate per costruire diaframmi plastici, costituiscono materiali speciali che hanno il fondamentale obiettivo della protezione di particolari siti, dovendo fornire prestazioni caratterizzate da bassa conducibilità idraulica e, allo stesso tempo, da elevati valori di resistenza e buon comportamento elastico. Il comportamento, soprattutto idraulico di queste miscele, è stato ampiamente studiato in laboratorio e in sito (Vespo *et alii*, 2021). Escludendo i diaframmi che hanno la parte sommitale emergente al di sopra del piano campagna, con conseguente esposizione di una porzione dell'opera agli agenti atmosferici (Jefferis, 1981; Opukumo *et alii*, 2021; Grisolia *et alii*, 2000), meno frequenti sono gli studi e le ricerche orientate a verificare lo stato di conservazione e di efficienza idro-meccanica nel tempo dei diaframmi plastici che si trovano interamente posizionati al di sotto del piano campagna. Nella presente nota, è stato esaminato il caso del diaframma plastico realizzato nell'area di Malagrotta (Roma, Italia), tra settembre 1988 e novembre 1989, con l'obiettivo di confinare i Rifiuti Solidi Urbani provenienti, per lo più, dalla città di Roma (Italia). Verificare il suo livello di efficienza è ora opportuno, specie a causa delle indagini giudiziarie che ipotizzano una perdita di efficienza di questa importante opera, in termini di conducibilità idraulica e comportamento elastico.

Per fare chiarezza al riguardo sono stati utilizzati i dati disponibili, ricavati da una serie di test idraulici effettuati nel sito di Malagrotta in prossimità del perimetro del diaframma plastico. E' stato possibile valutare le condizioni di flusso idraulico e gli spostamenti elastici teorici del diaframma (freccia e area della deformata) corrispondenti alle variazioni di carico. I risultati ottenuti sono stati analizzati attraverso l'equazione della linea elastica, utilizzando anche i dati contenuti nel progetto del diaframma plastico (Calenda & Esu, 1988). Dal confronto tra questi dati sperimentali e i risultati ottenuti dalle valutazioni analitiche, elaborati anche attraverso confronti statistici, sono emersi dati complessivamente tranquillizzanti che segnalano un eccellente stato di conservazione dell'opera e della sua efficienza, ad oltre 34 anni dalla sua realizzazione.

ABSTRACT

The MSW landfill of the city of Rome, one of the largest in Europe, was created in the area of Malagrotta. Between the 1950s and the early 1960s, this area hosted important sand and gravel quarries, which supplied aggregates for construction projects, such as those necessary for the rapid urban expansion of Rome after the second world war.

The area has a complex stratigraphy, schematically consisting (from top to bottom) of volcanic deposits, sands, gravels, and very compact gray-blue clays.

This geological setting, with cavities from the previous quarrying of large volumes of aggregates (estimated at over 200 × 106 m^3 in 1987), offered an ideal site for MSW disposal.

Remediation and safe confinement projects were undertaken at the landfill site after the issuing of Decree of the President of the Republic 915/82 of 10 September 1982, transposing three European Directives, including Council Directive 75/442/EEC of 15 July 1975 on waste, into the Italian legislation. From a financial and technical-scientific viewpoint, the most important project to make the landfill compliant with the new legislation was the construction of a hydraulic sealing wall around the internal subareas of the landfill that would accommodate MSW. The wall consisted in a plastic diaphragm of variable depth (Fig. 1).

This is one of the major barrier walls built in the world for the confinement of MSW landfills (Table 1).

As part of the activities undertaken at the Malagrotta landfill site, we investigated the functional efficiency of the diaphragm. Several in situ tests were thus planned and implemented. This paper analyses the results of hydraulic stress tests carried out in appropriate sections, provided with piezometers and other measuring instruments making part of the system for monitoring the entire surface area of the landfill (161 ha).

Figure 3 is a sketch of the section used for hydraulic tests, representing the entire confinement system (Fig. 2).

The entire set of data confirms the efficiency of the confinement system examined.

The results obtained, by imposing Darcy's solution based on a reductio ad absurdum argument, demonstrates that the cement-bentonite diaphragm is totally "impermeable" and thus fully suitable for performing the function for which it was designed and built (Prestininzi & Romagnoli, 1991). The data shown in Table 2 corroborates this assumption, i.e. the hydraulic heads in V_7 and in Z_7 are linked by a linear proportionality ratio, connected with a transfer of energy (pressure).

The findings from our hydrogeological analysis and the application of Darcy's law were validated by a mechanical analysis of the elastic behaviour of the diaphragm, made up of a cement-bentonite mixture. The results of the application of the equations of the elastic line revealed that the undrained behaviour of the soil-diaphragm system was in line with our analyses based on experimental data from hydraulic tests and statistical tests.

By using Equations (3) and (4), we computed the values u_{max} and Au_{max} for all the time steps ti. Statistical processing of the data enabled us to compare all the available results: piezometric heads in V_7, piezometric heads induced in Z_7, arrow umax ($x = 0$), and surface area Au_{max} acting on the diaphragm. In particular, the comparison highlighted their mutual relationships under the various conditions of stress q, thereby validating the linear proportionality of the diaphragm displacement and the origin of the piezometric changes ΔHZ_7. Indeed, the data of Tables 2 and 3 shows the linear proportionality of ratios (V_7/Z_7) and of changes in hydraulic head with the data connected with the diaphragm displacement, $\Delta H(Z_7)/[(Au)/(u_{max}\ (x = 0)]$.

The analysis of these results confirmed what we had observed during hydraulic investigations: the behaviour of the system, subjected to hydraulic stress tests, proved to be typical of undrained systems, which respond to stress changes with exchanges of energy and induced deformations at constant volume (Figs. 3, 5, 6 a) and b)).

After more than 34 years since its construction, the cement-bentonite plastic diaphragm retains an excellent hydromechanical efficiency, allowing it to perform its hydraulic sealing and mechanical elastic behaviour function in the future.

Keywords: *Municipal solid waste, cement-bentonite diaphragm, elastic behaviour, plastic diaphragm*

INTRODUCTION

Cement-bentonite mixtures are special materials that are employed to build plastic diaphragms. Their chief purpose is to protect specific sites, thanks to their low hydraulic conductivity and high strength values and good elastic behaviour. Extensive laboratory and field studies have been focused on the hydraulic behaviour of these mixtures. However, apart from diaphragms with their top protruding above ground level and thus exposed to weather agents (Jefferis, 1981; Opukumo *et alii*, 2021; Vespo *et alii*, 2021; Grisolia *et alii*, 2000), diaphragms lying entirely below ground have been less frequently investigated in terms of assessment of their long-term hydraulic and mechanical efficiency.

This paper deals with a plastic diaphragm that was built in the area of Malagrotta (Rome, Italy) between September 1986 and November 1987, with a view to confining Municipal Solid Waste (MSW), mostly originating from the city of

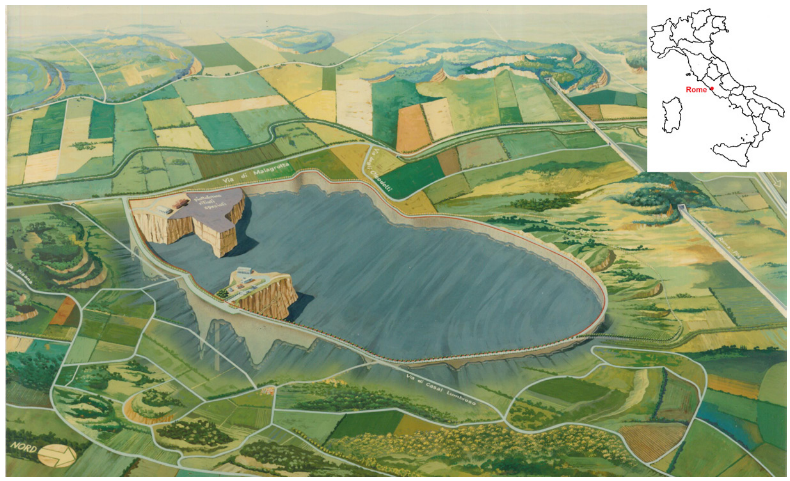

Fig. 1 - Malagrotta landfill. Perspective view of the plastic diaphragm. Eastern part of the area: trend of the top of the basal clays and configuration of the plastic diaphragm (modified from: Roma Capitale, 2017)

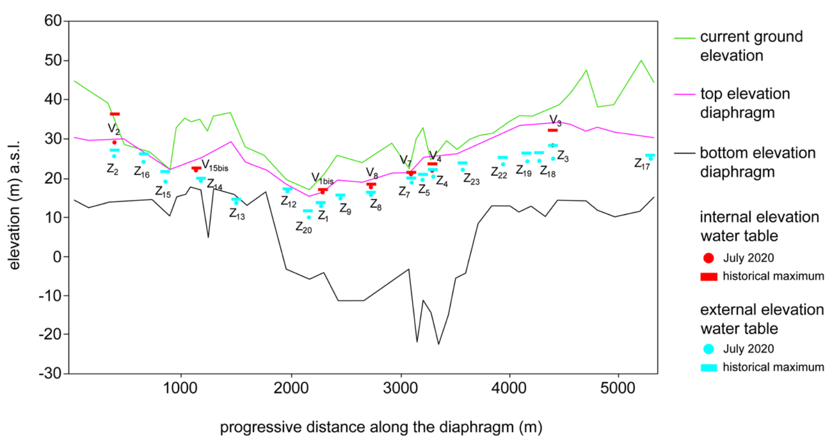

Fig. 2 - Contact between the diaphragm and the basal clays. The figure also shows the internal (V) and external (Z) monitoring piezometers, the topographic surface, and the top of the diaphragm. Elevations above sea level (a.s.l.) plotted against distances measured along the perimeter of the diaphragm

Excavation (m^3)	Length (m)	Circumscribed surface (m^2)	Depth (m)	Depth $V_7 - Z_7$ *L* (m)	Average thickness (m)	Surface diaphragm (m^2)	Hydraulic cement (quintals)	Bentonite (quintals)
2.3 × 10^6	5423	161 × 10^4	from −8 to −48	24.5	1	110782	177203	68120

Tab. 1 - Geometric and structural features of the diaphragm. Construction time: 2 years.(From, Calenda & Esu, 1988)

Rome. Assessing the level of efficiency of this important structure has become imperative, considering the current judicial investigations over its alleged loss of efficiency in terms of hydraulic conductivity and elastic behaviour. To gain an improved understanding of the issue, use was made of data available from a set of previous hydraulic tests carried out at the Malagrotta site, along the perimeter of the plastic diaphragm. Hydraulic flow conditions and theoretical elastic displacements of the diaphragm were thus assessed (arrow and surface area of the deformed shape). Results were analysed via both the equation of the elastic line and the design data of the plastic diaphragm (Calenda & Esu, 1988). A comparison between this experimental data and the findings from our theoretical assessments, processed with statistical methods, yielded an overall reassuring picture, i.e. the excellent hydromechanical efficiency of the structure after more than 34 years since its construction.

THE MALAGROTTA LANDFILL

The MSW landfill of the city of Rome, one of the largest in Europe, was created in the area of Malagrotta. Between the 1950s and the early 1960s, this area hosted important sand and gravel quarries, which supplied aggregates for construction projects, such as those necessary for the rapid urban expansion of Rome after the second world war, and for major infrastructure, e.g. the runways of Leonardo da Vinci airport at Fiumicino (Rome). The area has a complex stratigraphy, schematically consisting (from top to bottom) of volcanic deposits, sands, gravels, and very compact gray-blue clays. These clays of Plio-Pleistocene age belong to a significant geological formation and, in the local stratigraphic succession, they were assumed to be the basic lithology. Their thickness is considerable and, in the area investigated, it exceeds 100 m. Their contact with the overlying sands and gravels occurs at depths ranging from a few to tens of metres from ground level (Galeotti *et alii*, 1990; Carboni, 1980). This geological setting, with cavities from the previous quarrying of large volumes of aggregates (estimated at over 200 × 10^6 m^3 in 1987), offered an ideal site for MSW disposal.

Remediation and safe confinement projects were undertaken at the landfill site after the issuing of Decree of the President of the Republic 915/82 of 10 September 1982, transposing three European Directives, including Council Directive 75/442/EEC of 15 July 1975 on waste, into the

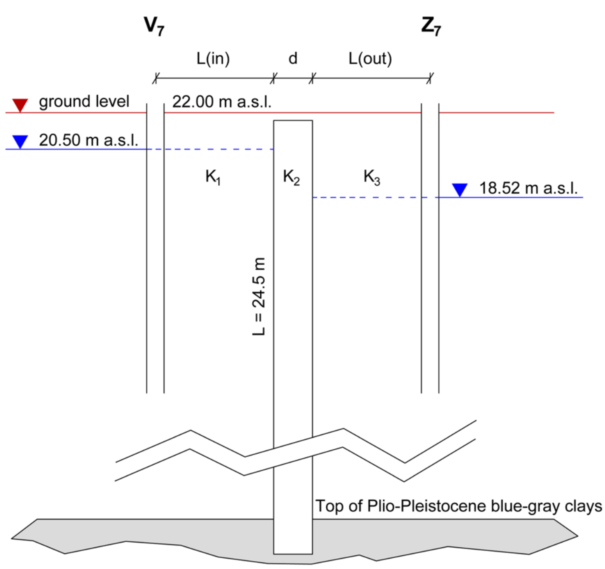

Fig. 3 - Not to scale. Location of piezometers V_7, Z_7, and of the cement-bentonite diaphragm under the initial conditions t_0 (no pumping). The figure shows the distance L = 8 m between the piezometers; the portions of soil L(in) and L(out) included between the piezometers and the diaphragm; the permeability coefficients k_1 and k_3 of the portions of soil L(in) and L(out), with average values of 10^{-5} m/s; the cement-bentonite diaphragm (average thickness d = 1 m); the design permeability coefficient K_2, with values not exceeding 10^{-9} m/s; and the diaphragm depth L = 24.5 m. The bottom line simulates the occurrence of the compact and "impermeable" gray-blue clays of Plio-Pleistocene age, into which the deep part of the diaphragm is stuck for about 2 m

Italian legislation. From a financial and technical-scientific viewpoint, the most important project to make the landfill compliant with the new legislation was the construction of a hydraulic sealing wall around the internal subareas of the landfill that would accommodate MSW. The wall consisted in a plastic diaphragm of variable depth (Fig. 1). The diaphragm thus intersected the underlying gray-blue clays at different depths (Fig. 2). For construction of the diaphragm, use was made of a hydraulic cement-bentonite mixture. This is one of the major barrier walls built in the world for the confinement of MSW landfills (Table 1).

HYDRAULIC CONDITIONS

As part of the activities undertaken at the Malagrotta landfill site, we investigated the functional efficiency of the diaphragm. Several in situ tests were thus planned and implemented. This paper analyses the results of hydraulic stress tests carried out in appropriate sections, provided with piezometers and other measuring instruments making part of the system for monitoring the entire surface area of the landfill (161 ha). As pointed out about, this area is confined by a cement-bentonite plastic diaphragm. The resulting data was integrated with data acquired from:

- studies for the construction of the plastic diaphragm (Calenda & Esu, 1988);
- specific scientific literature (Galeotti *et alii*, 1990; Grisolia *et alii*, 2000);
- the Malagrotta area characterisation plan (*Piano di Caratterizzazione della Discarica di Malagrotta,* Roma Capitale, 2017);
- from an archival data record built over time through surveys and analyses, but also through daily data collected from monitoring points present along the entire perimeter of the diaphragm.

The entire set of data confirms the efficiency of the confinement system examined.

Figure 3 is a sketch of the section used for hydraulic tests, representing the entire confinement system (Fig. 2). Along this section, tests were carried out with the specific goal of defining the hydraulic and mechanical efficiency of the cement-bentonite hydraulic sealing. Piezometer V_7, inside the landfill area, was separated from piezometer Z_7 by the interposed diaphragm. Thus, Z_7 was located outside the landfill area. Measurements of hydraulic heads in V_7 and effects in Z_7, expressed in metres above sea level (m a.s.l.), were carried out during the entire testing period from t_0 to t_{12} (Fig. 5). The different time steps were directly associated with pumping activities, alternating with no-pumping intervals. Changes in the internal piezometric head were expressed by the values of hydraulic head recorded in V_7. The monitoring piezometer Z_7

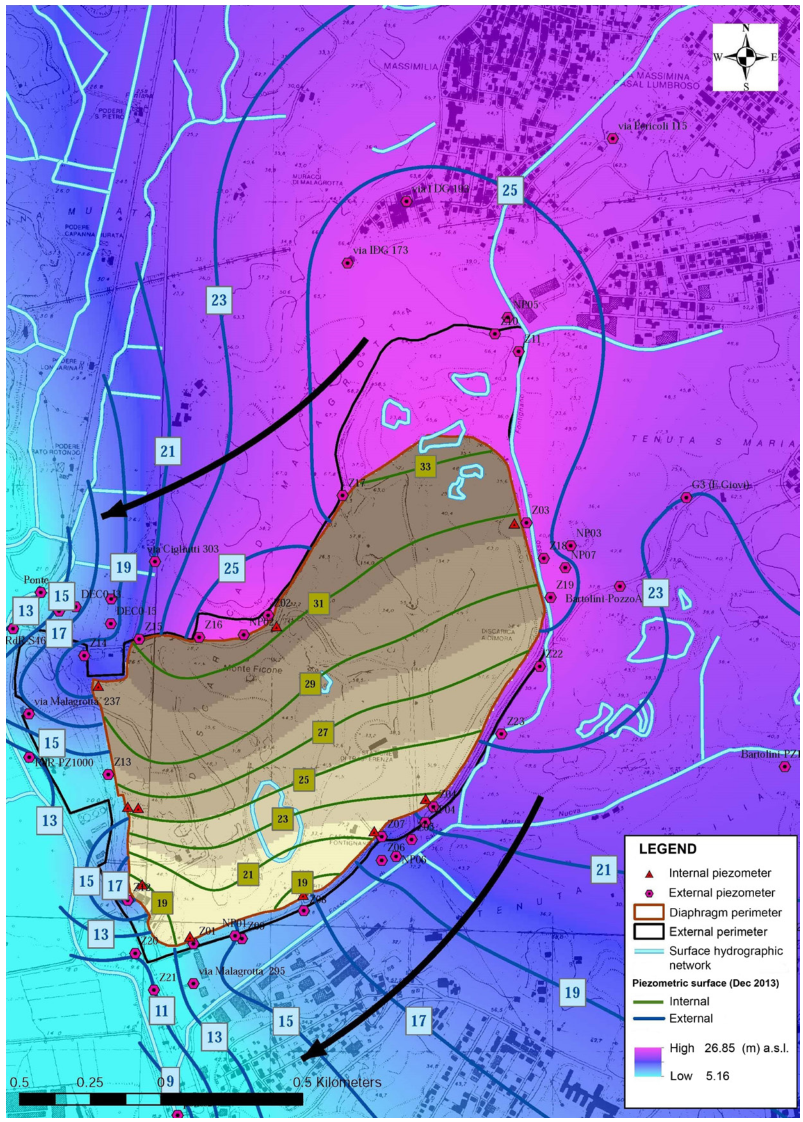

Fig. 4 - Hydraulic conditions in the Malagrotta area. Location of the plastic diaphragm and trend of isopiestic lines "internal" and "external" to the diaphragm. Location of internal and external monitoring piezometers (modified from Piano di Caratterizzazione, Roma Capitale (2017)

was placed outside the diaphragm. For all the time steps t_0-t_{12}, the external hydraulic heads recorded in Z_7 were constantly lower than the internal ones recorded in V_7. This experimental finding was in line with the data recorded over time by internal (V_i) and external (Z_i) piezometers along the entire perimeter of the diaphragm (Fig. 2).

INVESTIGATION APPROACH

As the motion of fluids through porous media between two generic points in a soil is governed only by the difference in their hydraulic head, studies quantifying the water flow in a soil make reference to Darcy's law. Using this law, we can identify the fundamental links that exist between the characteristics of motion and, in particular, flow velocity on the one hand, and the properties of a soil and the head loss between the points considered on the other hand. The study of a unidimensional laminar flow of water in a soil makes it possible to measure the discharge per unit area, which is directly proportional to the head loss between two points and inversely proportional to the length of the flow path. In practice (see Fig. 3), the discharge Q per unit area can be defined by the apparent or nominal seepage velocity.

Assessing the overall behaviour of the local hydrogeological system was a central element of the hydraulic tests carried out on section V_7-Z_7. The boundary conditions of this system (Fig. 3) were as follows:

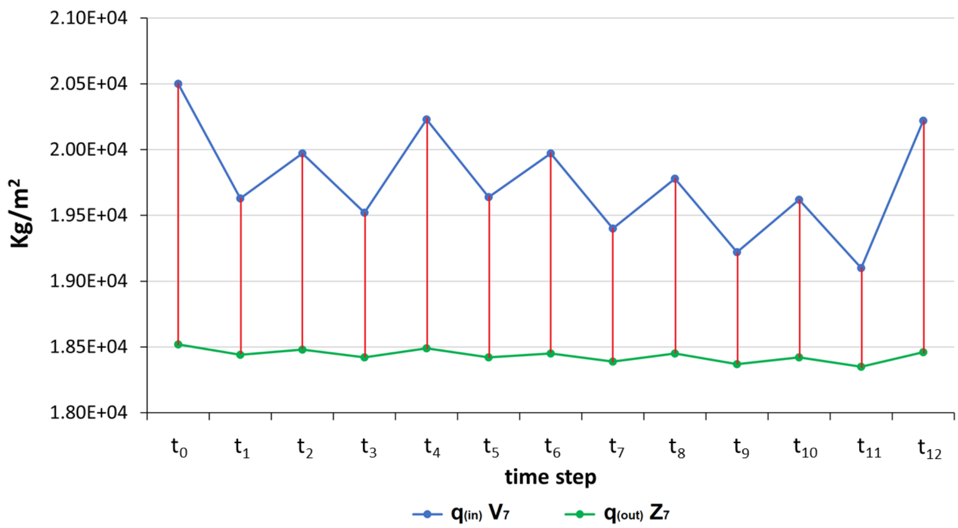

Fig. 5 - Hydraulic tests: trend of the piezometric head in V_7 and effects recorded in Z_7. t_0 = 15 July 2020. The graph shows 12 time steps (t_1-t_{12}) starting from t_0, the hydraulic heads (m a.s.l.) automatically recorded by piezometer V_7, and the effects induced in piezometer Z_7, located outside the cement-bentonite diaphragm. Note that the external piezometric head in Z_7 is constantly below the head measured in V_7 (modified from "Relazione finale incidente probatorio")

1. the cement-bentonite diaphragm with a thickness of 1 m and a length L = 24.5 m;
2. its internal lateral boundaries, consisting of the soil deposits occurring between V_7 and the diaphragm, *L(in)*;
3. its external lateral boundaries, consisting of the soil deposits occurring between the diaphragm and Z_7, $L_{(out)}$;
4. its upper and lower boundaries, consisting of the topographic surface and the top of the "basal" clays, respectively; the latter clays are known for their physico-mechanical properties that qualify the related clayey formation as "impermeable"; they have thicknesses of hundreds of metres and a grain size composition consisting of over 40% by weight of silty clays, with a very high clayey fraction < 2 μ (Galeotti *et alii*, 1990).

Hydraulic surveys were carried out with reference to the graphs of Figs. 3, 4, and 5.

HYDROGEOLOGICAL ANALYSIS

Figure 5 depicts the findings from the tests carried out on the section shown in Fig. 3. The graph in the figure allowed us to make useful assessments of the behaviour of the above-mentioned hydrogeological system, in particular to test the assumption that the cement-bentonite diaphragm might be penetrated by fluids, driven by the gravity-controlled hydraulic head.

Withdrawal tests were carried out from wells placed inside the cement-bentonite diaphragm. During the tests, because of the transmissivity of the local soils, we could change the hydraulic head near the measuring section. These changes were recorded through piezometer V_7. Simultaneous reading of piezometer Z_7 (Fig. 5) demonstrated unequivocally that the interposed diaphragm inhibited groundwater flow from the inside to the outside and vice versa. Indeed, we should not be misled by the minimum changes in piezometric heads recorded externally, in piezometer Z_7, in response to changes recorded in V_7. In this regard, we should point out that the two heads (internal and external) were always different and that the internal piezometric head was always higher than the external one. As a result of withdrawal cycles, internal groundwater level decreases/increases of the order of 1 m were accompanied by groundwater level decreases/increases of the order of 1 cm outside the diaphragm. However, these minimum changes were merely indicative of changes in pressure and not in hydraulic flow. Indeed, even by using a *reductio ad absurdum*, it would be impossible to assume water flow through the diaphragm, because the internal water level would always remain significantly higher than the external one. Moreover, as groundwater flow is controlled by gravity (hydraulic gradient), groundwater cannot flow from lower to higher levels. In the opposite instance, i.e. by assuming a flow from the inside to the outside, the external levels would receive water and thus show a tendency to increase and not to decrease, albeit to a very small extent: without an increase in the external piezometric level, there would be no flow.

These conditions have a rational scientific explanation if we consider the behaviour of closed systems. Basically, closed systems can exchange energy (in this instance, pressure) but not matter (in this instance, water). As displayed in the experimental graph of Fig.

5, the head changes observed in V_7 and Z_7 have an instantaneous temporal response ($\Delta t_i = 0$) at each time step. This is typical of closed systems, which do not exchange matter. In geological engineering, this behaviour is known as undrained behaviour, in which pressure changes induce changes in a soil mass or in a structure, at constant volume.

Time steps	Hydraulic head V_7 (m a.s.l.)	Hydraulic head Z_7 (m a.s.l.)	V_7/Z_7	Standard deviation
t_0	20.50	18.52	1.11	0.02
t_1	19.63	18.44	1.15	0.02
t_2	19.97	18.48	1.11	0.02
t_3	19.52	18.42	1.10	0.02
t_4	20.23	18.49	1.14	0.02
t_5	19.64	18.42	1.16	0.02
t_6	19.97	18.45	1.12	0.02
t_7	19,40	18,39	1.10	0.02
t_8	19.78	18.45	1.12	0.02
t_9	19.22	18.37	1.10	0.02
t_{10}	19.62	18.42	1.15	0.02
t_{11}	19.10	18.35	1.10	0.02
t_{12}	20.22	18.46	1.15	0.02

Tab. 2 - Proportionality ratio between the hydraulic heads in V_7 and Z_7, occurring on the walls of the "internal and external" cement-bentonite diaphragm at each time step. The statistical processing of the data shows linear proportionality, absence of water exchanges, and undrained behaviour of the system investigated

ANALYSIS WITH THE APPLICATION OF DARCY'S LAW

Our "hydrogeological" analysis was substantiated by Darcy's law, which applies to all two-phase systems (consisting of a solid phase and of a liquid phase, regarded as not compressible).

Considering the geometric conditions measured along the section V_7 - diaphragm - Z_7, we applied Darcy's law with:

- L = 8 (m): distance between V_7 and Z_7;
- D = average thickness of the diaphragm, equal to 1 (m);
- ΔH = initial piezometric head at t_0, equal to (20.50-18.52) = 1.98 m (14 July 2020);
- $i_t = \Delta H/d$ hydraulic gradient, calculated for each time step t_i, with i ranging from t_0 to t_{12}; note that the piezometric head in V_7 at each time step t was always higher than the piezometric head in Z_7 (Fig. 5);
- $K_1 \approx K_3$ = Darcy's permeability coefficients of soils occurring between V_7 and the diaphragm, and between Z_7 and the diaphragm, assumed to be equal to 10^{-4}-10^{-5} (m/s);
- K_2 = Darcy's permeability coefficient of the diaphragm, with design values not higher than 10^{-9} (m/s).

Both stratigraphic data and previous surveys, especially those needed for the Malagrotta site characterisation plan, indicated that $K_1 \approx K_3 >>> K_2$. Therefore, we assumed that $k_2/(k_1 = k_3) \approx 0$. Under these conditions, Darcy's flow along section L (8 m) would lose all of its head along the section of the diaphragm having the

permeability coefficient K_2, i.e. along the path $d = 1$ m. Thus, the hydraulic gradient would be equal to $i = \Delta H/d$ and the flow velocity would be $V = k_2 \cdot i$.

Considering a surface A, crossed by a water flow along the path between V_7 and Z_7 (1 m^2), the amount of fluid crossing section A at each time step shown in Fig. 5, i.e. at t_0, $t_1 \ldots\ldots t_{12}$, would be $Q = A \cdot k_2 \cdot it = A \cdot V$. We also resorted to a *reductio ad absurdum*, i.e. imposing a velocity consistent with physical conditions in the section considered, i.e. distance $d = 1$ m and fluid travel time consistent with the data recorded in the reference piezometers of Fig. 5: at each time step t_i, the time of departure of the flow from V_7 and its time of arrival at Z_7 would coincide, so that the difference between the time of departure and the time of arrival would be equal to $\Delta t = (t_{i(in)} - t_{i(out)}) = 0$.

Hence, the apparent flow velocity would be $V = L/\Delta t = 8/(0) = \infty$. If velocity takes on an infinite value, then for the relationship $V = k_2 \cdot i$ to be true, it should be expressed as $V = k_2 \cdot i = \infty = k_2 \cdot \Delta H/d$. Recalling that the hydraulic gradient $i = H/d$ takes on the value $0 < i < \infty$, to validate Darcy's equation, k_2 should be equal to ∞:

$$V = \frac{L}{\Delta t} = \frac{8}{0} = k_2 \cdot i = \infty \cdot \Delta H/d \text{ (non-real result)}$$

This *non-real result*, obtained by imposing Darcy's solution based on a *reductio ad absurdum* argument, demonstrates that the cement-bentonite diaphragm is totally "impermeable" and thus fully suitable for performing the function for which it was designed and built (PRESTININZI & ROMAGNOLI, 1991). The data shown in Table 2 corroborates this assumption, i.e. the hydraulic heads in V_7 and in Z_7 are linked by a linear proportionality ratio, connected with a transfer of energy (pressure), as shown in Tab 2.

ANALYSIS OF THE DEFORMED SHAPE OF THE DIAPHRAGM

The findings from our hydrogeological analysis and the application of Darcy's law were validated by a mechanical analysis of the elastic behaviour of the diaphragm, made up of a cement-bentonite mixture. The results of the application of the equations of the elastic line revealed that the undrained behaviour of the soil-diaphragm system was in line with our analyses based on experimental data from hydraulic tests and statistical tests.

Time steps	ΔH (Z_7) (± m)	U_x (x=0) Arrow ± (m)	ΔAu (± m²)	ΔH (Z_7)/ ($\Delta Au/u_x$ (x = 0))	Standard deviation
t_0	0.00	0.000	0.00	0.00	0.00
t_1	−0.08	−0.036	−0.36	−0.01	0.007
t_2	0.04	0.014	0.14	0.00	
t_3	−0.06	−0.019	−0.18	−0.01	
t_4	0.07	0.029	0.29	0.01	
t_5	−0.07	−0.024	−0.24	−0.01	
t_6	0.03	0.014	0.14	0.00	
t_7	−0.06	−0.023	−0.23	−0.01	
t_8	0.06	0.016	0.16	0.01	
t_9	−0.08	−0.023	−0.23	−0.01	
t_{10}	0.05	0.016	0.16	0.01	
t_{11}	−0.07	−0.021	−0.21	−0.01	
t_{12}	0.11	0.046	0.46	0.01	

Tab. 3 - Statistical linearity of the proportionality ratio ΔHZ_7/(C/ux (x= 0), obtained through the link between the change in hydraulic head (ΔHZ_7) and the displacements of the diaphragm (arrow ux (x = 0) and (ΔAu), induced by the internal hydraulic head (V_7).

Using Figs. 3, 6a, and 6b, we developed the equation of the elastic line to investigate the parameters governing the displacements of the system considered, which were controlled by the presence of the diaphragm.

Based on the data already used for hydraulic investigations, derived from the measurement of piezometric heads in V_7, and expressing all the values in kg and m, we had:

- q = head (kg/m²), evenly distributed and acting on the cement-bentonite diaphragm wall;
- L = free length of the diaphragm (m), equal to 24.5 m, near section V_7-Z_7;
- E = Young's modulus of the cement-bentonite diaphragm, taken to be equal to 1.4×10^{10} kg/m² (Jefferis, 1981; Opukumo *et alii*, 2021; Paggi *et alii*, 2013);
- J = moment of inertia, equal to 0.083 m⁴, for a 1 m wide diaphragm.

Through the equation of the elastic line, we defined the displacement *u(x)* (m) of the diaphragm between its top position (x = 0) and its bottom position (x = 24.5), and the corresponding surface area Au between deformed and undeformed shape.

$$u_x = \frac{q\,x^4}{24EJ} - \frac{q\,L^3\,x}{6\,E\,J} + \frac{qL^4}{8EJ} \qquad (1)$$

$$Au = \int_L^0 \left(\frac{qx^4}{24EJ} - \frac{qL^3x}{6Ej} + \frac{qL^4}{8EJ}\right)dx \qquad (2)$$

a) from Eq. (1), we calculated the maximum displacement recorded at the diaphragm top, arrow u_{max} (x = 0), for each value of q measured in V_7 and for the various time steps t_i:

$$U_{\max}(x=0) = \frac{q\,L^4}{8EJ} \qquad (3)$$

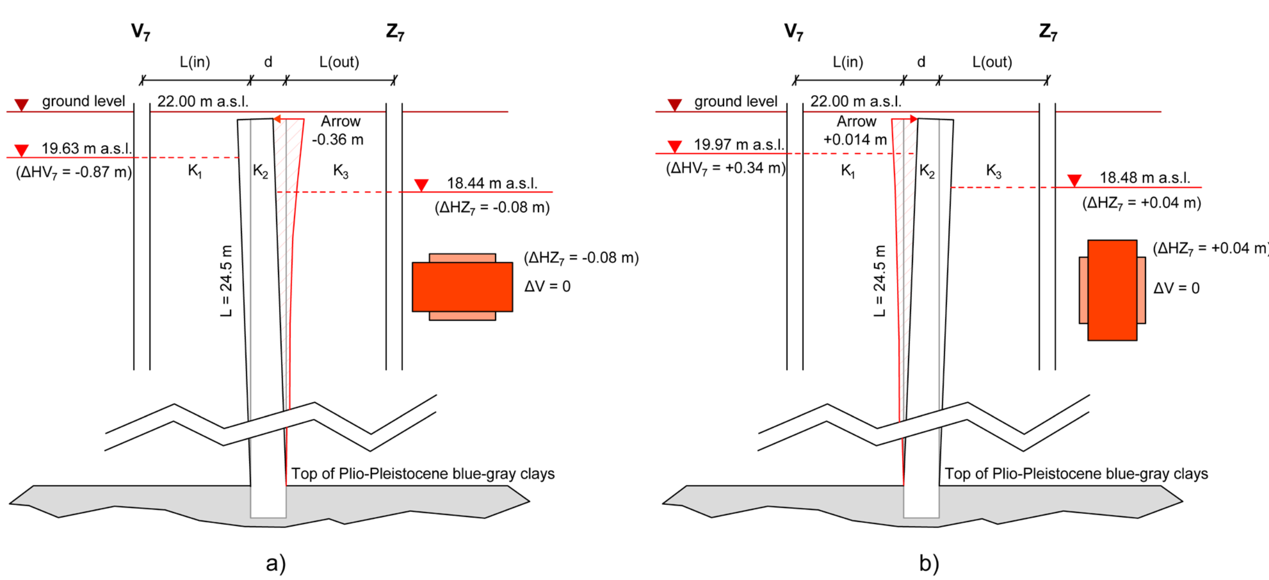

Fig. 6 - The link between the change in hydraulic head and the values of the arrow and surface area of the deformed shape is shown by the linearity of the $\Delta H(Z_7)/(\Delta Au/u_{max}(x{=}0)$ ratio. The figures simulate the overall displacement of the diaphragm, representing the deformation distributed between V_7 and Z_7

b) from Eq. (2), give the value of the surface area $Au_{(max)}$ related to the displacement of the diaphragm and based on the value of $u_{(max)}$ $(x = 0)$:

$$Au_{max} = \frac{q\,L^5}{120\,E\,J} + \frac{q\,L^5}{12\,E\,J} + \frac{q\,L^5}{8\,E\,J} = \frac{q\,L^5}{20\,E\,J} \qquad (4)$$

By using Equations (3) and (4), we computed the values u_{max} and Au_{max} for all the time steps t_i. Statistical processing of the data enabled us to compare all the available results: piezometric heads in V_7, piezometric heads induced in Z_7, arrow u_{max} $(x = 0)$, and surface area Au_{max} acting on the diaphragm. In particular, the comparison highlighted their mutual relationships under the various conditions of stress q, thereby validating the linear proportionality of the diaphragm displacement and the origin of the piezometric changes ΔHZ_7. Indeed, the data of Tables 2 and 3 shows the linear proportionality of ratios (V_7/Z_7) and of changes in hydraulic head with the data connected with the diaphragm displacement, $\Delta H(Z_7)/[(Au)/(u_{max}\ (x = 0)]$.

The analysis of our results confirmed what we had observed during hydraulic investigations: the behaviour of the system, subjected to hydraulic stress tests, proved to be typical of undrained systems, which respond to stress changes with exchanges of energy and induced deformations at constant volume (Figs. 3, 5, 6 a) and b)).

CONCLUSIONS

Investigations were carried out in the area of Malagrotta (Rome, Italy), accommodating a large MSW landfill, with a view to assessing the hydromechanical efficiency of the plastic diaphragm that had been put in place between 1986 and 1987. The investigations showed that the diaphragm can ensure the total hydraulic discontinuity of the landfill area, as set forth in Council Directive 75/442/EEC of 15 July 1975 on waste. This large-sized and very important structure (Figs. 1 and 2) forms an environmental safety barrier around the 161 ha landfill. For safety purposes, the individual subareas of the landfill, located inside the diaphragm, are equipped with ordinary confinement structures, as prescribed for MSW landfills.

Our hydrogeological and mechanical analyses demonstrated that the behaviour of the plastic diaphragm is in line with its design and test data. Our overall results, statistically processed, substantiated the efficiency of the diaphragm, as shown by the linearity of the proportionality ratios of V_7/Z_7 and $\Delta H(Z_7)/(\Delta Au/u_{max}\ (x = 0)$ (Tables 1 and 2).

After more than 34 years since its construction, the cement-bentonite plastic diaphragm retains an excellent hydromechanical efficiency, allowing it to perform its hydraulic sealing and mechanical elastic behaviour function in the future.

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