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Effect Of Water On Slope Stability And Investigation Of □ □w Drainage Techniques Applied To Sections Of Egnatia Odos.

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ABSTRACT: *This study is to explore the drainage possibility of physical and technical landslide slopes, with the help of draining projects implementation, which operate without energy consumption and contribute significantly to their stabilization. We investigated the function, the general assumptions of application and the construction methodology of these new drainage techniques, i.e. the Drainage Gravel Piles. In addition, we investigated their applicability in a landslide area of Egnatia Odos: Section 3.1 (Peristeri - Anthochori), Area B (1+100-1+600), with the unsaturated background of a buried riverbed, and calculated the most suitable distance between them, in order to drain it. After observing their function and evaluating the results of our study, we reached some important conclusions such as: 1. The positive effect of drainage gravel piles on the drainage of a landslide area, in the presence of high water-bearing capacity aquifers within these materials and the existence of unsaturated permeable background, through the attainment of draining these landslide materials in this permeable background. 2. The groundwater drawdown and the reduction of pore pressure that they cause, in the landslide area, are inversely proportional to the distance between them and directly proportional to the depth which the landslide materials reach. 3. The drainage of a landslide area, highlighting failures in various positions without their hydraulic communication, is achieved by applying groups of drainage gravel piles in these sub-positions. 4. In the areas where landslide incidents are recurrently manifested and take up large areas, these drainage projects contribute to a greater extent than other measures to the stabilization of the situation and to further balance restoration.*

Keywords: *Drainage gravel piles, Landslide materials, unsaturated permeable background, Pumping tests, Drawdown, Landslide Stabilization.*

I. INTRODUCTION

Through the detailed description of the ground conditions and the effect of surface water and groundwater on mechanisms activating failures, the way in which the application of new drainage measures can alter local conditions, by reducing the pore pressure and inhibiting ground motions resulting in halting landslide phenomena, is investigated and additionally the operating principles of these new projects are analyzed. That is, we tried to attain without additional cost the same result as the one attained by pumping tests. That is to say achieve the draining of the landslide mass with the simultaneous channeling of the leachate in underlying unsaturated aquifers and not in the ground surface by pumping. The investigation of the function of these new ground drainage techniques that were called Drainage Gravel Piles was performed under certain conditions which concerned:

- Having loose landslide ground materials.
- Having an unconfined aquifer formation in landslide materials and thus presence of impermeable underlying formation.
- Having an unsaturated aquifer underlying the impervious layer.

II. DRAINAGE GRAVEL PILES

2.1 Operating Principle

- The operating principle of the drainage gravel piles is based on the principle of the flow into water drilling works, in which the empirical methods of Dupuit and Thiem on pumping tests are applied for the calculation of their hydraulic parameters according to the type of the aquifer and the flow status.
- Darcy's law must apply and is expressed by the relationship: **$Q = kiF$** where:

Q = the water supply that flows through the cross-sectional area F in m^3/sec,
$i = h_1-h_2/ I$ = the hydraulic gradient along the water flow, where I the length of run,
k = the permeability coefficient of porous media in m/sec
F = the cross-sectional area vertically to water flow in m^2

- Drainage gravel piles are vertical drainage wells, filled with a graded gravel material (of a diameter of 5 to 20mm), washed and free of fine ingredients. The method is consisted in displacing a column of ground material on the spot and replacing it with gravel material, i.e. a gravel pile is created. Due to the high permeability of the gravel material in relation to the environment, the gravel piles function as vertical strainers facilitating the defusing of pore overpressures. Each well displays a drawdown aquifer cone (cone of depression) in its perimeter, for a specific impact radius, which concerns the drainage area. Therefore, the draining of a delimitated landslide area achieved through a specific grid or provision of drainage wells. The method is mostly applied to relatively cohesive, soft and compressible silt and clay soils.
- The monitoring of the drawdown is carried out by installed satellite piezometers of the drainage gravel piles, while the certification of ground motions is monitored by the pre-existing inclinometer measurements in each area. By the

application of the drainage wells both the drawdown, as well as the reduction of ground motions, is achieved. [1, 6, 7 & 14]

2.2 General assumptions of application

In order for the above to be applied we accept some general assumptions concerning [1, 7 & 13]:

- Having an unconfined aquifer of infinite extent
- Having a state of equilibrium
- Accepting homogeneity and isotropy throughout the length of the ground profile, as such in conjunction with the consideration state e.g. the landslide ground materials are considered heterogeneous at cm^3 level, at m^3 level, however, they are considered homogeneous and isotropic.
- Accepting the presence of a steady hydraulic load surrounding the project. Since this is theoretically impossible to be achieved, the situation becomes acceptable, with the assumption that the drawdown variation becomes negligible over time, after an extended pumping.
- The Thiem-Dupuit equation is therefore valid: $$Q=\frac{\pi k (h_2^2- h_1^2)}{\ln(r_2/r_1)} \quad (1)$$
- There is a continuation of the cone of depression to the water surface in the well. Even if this suggestion deviates from reality, but as we move away from the wellhead, these deviations are diminished, not affecting our calculations, since we are not interested in the precise form of the unconfined surface in close proximity to the drainage gravel piles.
- The vadose zone above the water table, the effect of the capillary zone, as well as the effect of the vertical component of velocity.
- Finally, we accept that the permeable background is practically horizontal, unsaturated and not under pressure.

2.3 Construction methodology

The general procedure is as follows (Fig. B1):

- we begin perforation with diameter 100cm, minimizing him progressively up to the end of drilling in Φ15´´ and placing them corresponding fence tube,
- following that, is the installation of galvanized filter tube, with grommet, Φ6″ and 4mm thick, with conical edge of 0.5m length and Φ6″ and blind the first 3 metres of the tube, while in the upper rim, of the lowest three-meters long filter tube, a piezometric galvanized tube is placed, heavy duty with grommet, Φ1½´´diameter,
- around the filter tube, the removal of the fence tube is performed and the filling of the vacuum with the graded gravel filter (5-20mm), with a simultaneous water circulation to prevent block formation,
- then, the protruding parts of the tubes are cut and in the heads of the gravel piles galvanized casings Φ10″ and concrete foundations with dimensions of 2X2X0.24m are placed,
- restoration of the surrounding area and coating using gravel,
- finally, a moat is constructed perimetrically for the collection of surface water.

- Daily measurements are carried out in the piezometers, at various stages of their construction, in order to label potential problems and to monitor their effectiveness.
- While, with the completion of the perforation works, test measurements concerning the level changes are performed by channeling water (2.5 m^3) through them, a procedure which operates as an evaluation criterion for their proper construction and function.

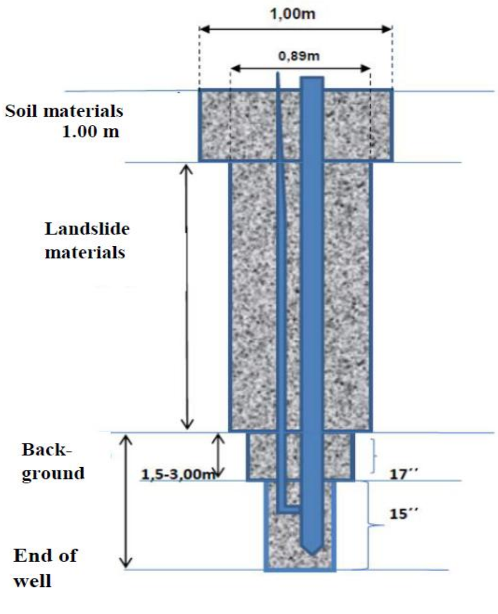


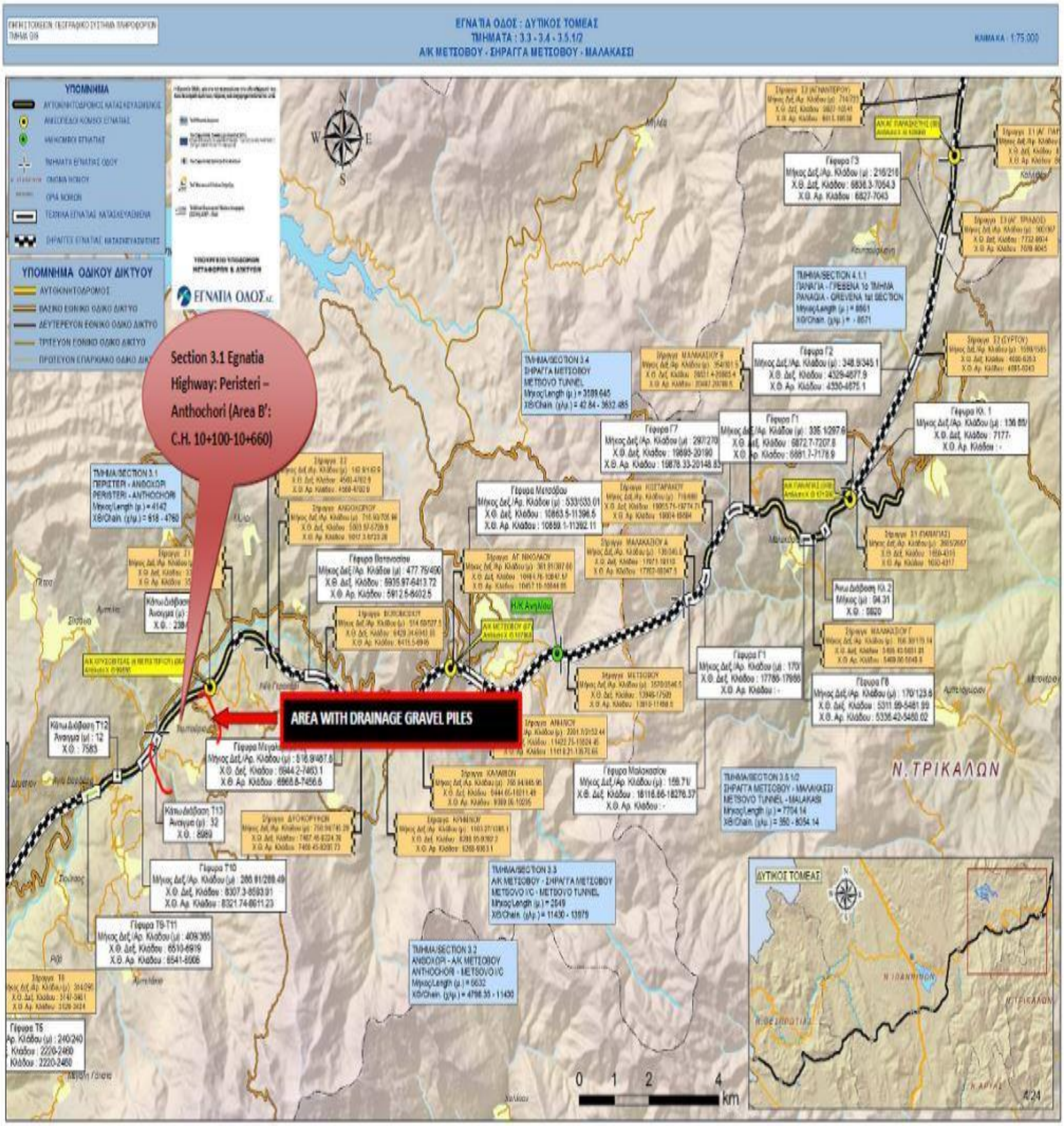
Figure B1: Schematic representation of the Drainage Gravel Piles.

III. AREA OF DRAINAGE GRAVEL PILES APPLICATION (SECTION 3.1 OF EGNATIA HIGHWAY, AREA B' –C.H. 1+100-1+900)

3.1 General data

In the category of major infrastructure projects all the highways across Europe are included and part of this trans-European transportation network is also Egnatia Highway. It happens to be one of the most difficult engineering projects. The Igoumenitsa port is its starting point and has a total length of about 680 km to Alexandroupoli and about 780 km to Ormenio. The special geotechnical problems (landslide areas) that were found at the opening up of the Highway, are rather remarkable and combined with the intense mountainous terrain, make the situation even more difficult. The Peristeri landslide is also one of them (Area B', from C.H. 1+100 to 1+900), which is found in Section 3.1 of Egnatia Highway. This project necessitated immediate treatment and stabilization in order for the road to be constructed (Map A1). It concerns a riverside landslide area, with Metsovitikos River its most important morphogenetic event. [2]

Map A1. Section 3.1 of Egnatia Highway:Peristeri – Anthochori, Area B' C.h. 10+100-10+660, (Area of application Drainage Gravel Piles)



3.2 Peristeri Landslide (Area B', 1+100 CH - 1+900 CH)

3.2.1 Geological structure and Geotectonic framework of the landslide area

More than one factors usually interact in order for landslides to occur. Soils consisting of alternations of several heterogeneous layers are more likely to display landslide phenomena, to others consisting of a single layer. Regions with alternations of permeable and impermeable formations, as well as zones of intense neotectonic activity, also display a similar behavior. Our study area is a combination of these, as it is structured with a large variety of formations concerning: **materials of anthropogenic origin** and **quaternary deposits** (current and past deposits of Metsovitikos River). In the highest (southernmost) part of the area the **formations of the geotectonic zone of Pindos** appear (limestone and hornstone formations and magmatic andesitic and cave rocks) obduct onto the **flysch formations of the Ionian zone** (average - to thin layer siltstones, sectioned and highly plicate in the highest section of the abutment and relatively of small thickness intercalations sandstone and conglomerate) (F. C1).

Photo C1: Landslide Area B pigeons (soil material instabilities).

This overthrust constitutes the main tectonic fact of the area. The area is divided into two sub-regions of different tectonic origin: the lower region, which extends from the bed of Metsovitikos River up to an altitude of about 800m and it is structured by flysch formations of the Ionian zone on which the landslides appear and the higher region (over 800m altitude) which is structured by obducted formations of Pindos. The main cause of the landslide development is the erosive process of Metsovitikos River. It is estimated that in past years it formed a deep engulfment towards the interior of the abutment, resulting in its undermining, in the development of landslide phenomena (in the degraded flysch formations) and in the displacement of the abutment to the north. The estimate inclination of the surface slope ranges between 20-22^{o}, in the highest landslide section, and between 10-15^{o} to its lower section (F. C2).

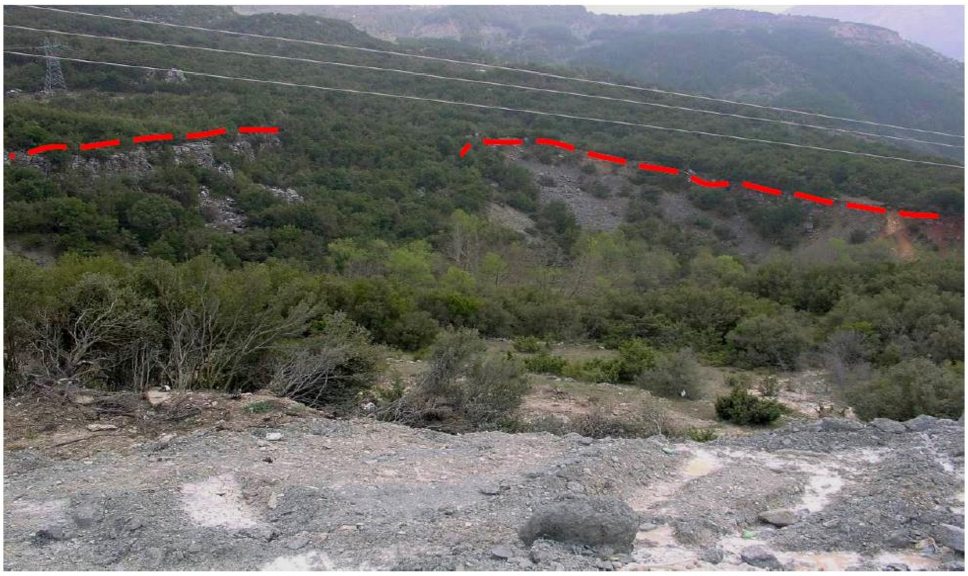
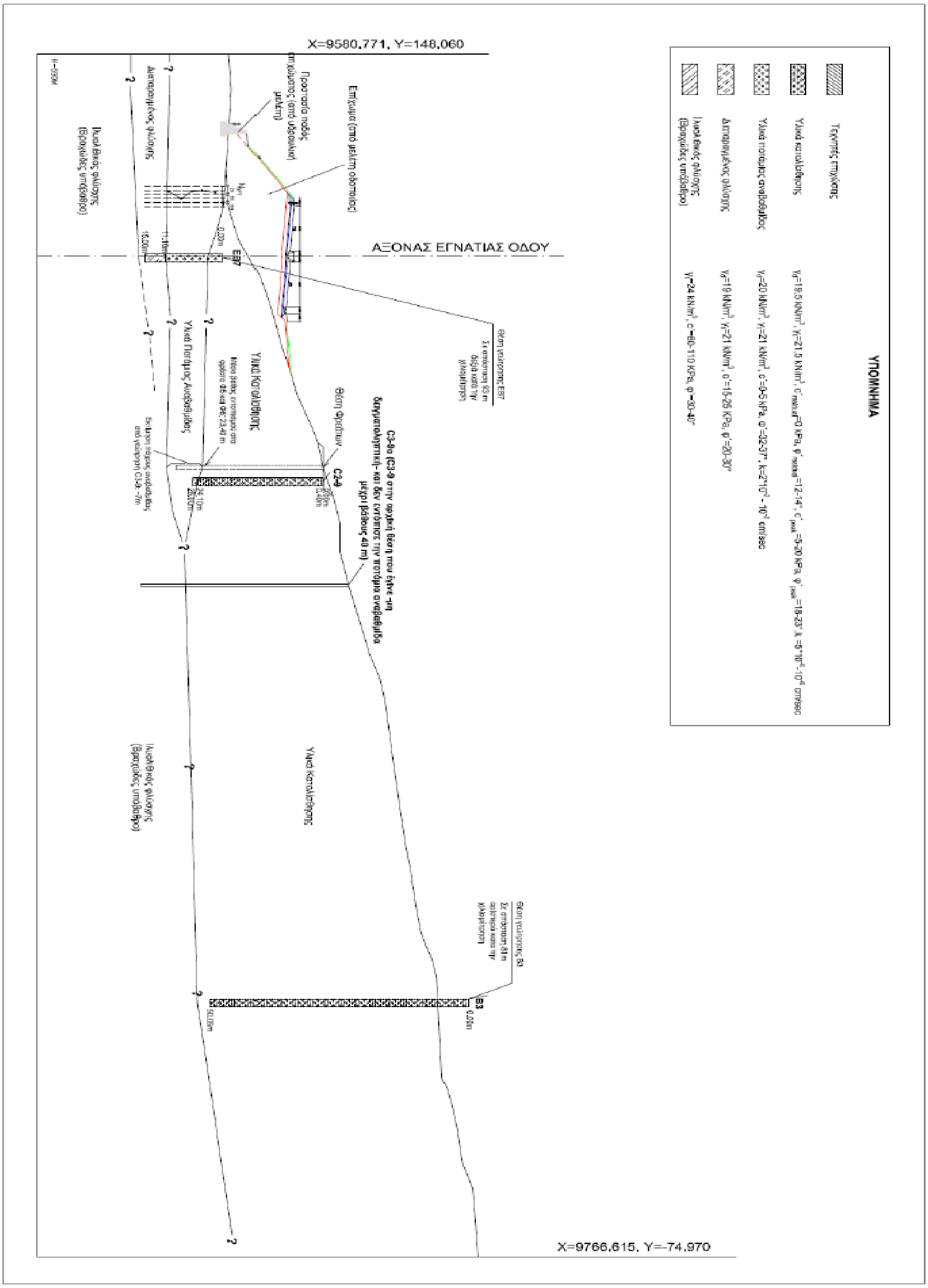


Photo C2: Landslide Peristeriou (the red dashed line shows the landslide).

A typical geological intersection is illustrated in Map A2. [4, 8, 11 & 12]

3.2.2 Hydraulic groundwater conditions and surface water indications

The formations that structure the area, from a hydrogeological point of view, are classified as of **very small to zero permeability** formations (landslide materials and flysch background which are found in the lower section of the abutment, from the Metsovitikos riverbed to an altitude of +800) and as of **average permeability** formations (small brecciaed limestone with green stones, intercalations of pelagic limestone, cherts and andesites). Finally, they are also classified as of **high permeability formations** (limestone formations and their side screes of Pindos zone and materials from the current and prior bed of Metsovitikos River, in the highest section of the abutment). Many water discharge points and springs of high supply have been spotted, especially in the highest section of the abutment, which overflow during the winter months, as well as evidence of stagnant waters (gathering of clayey silt materials in flats), especially in posts where phenomena of instability occur. [3, 4, 9 & 12]



Map A2: Geological intersection of the landslide's area (Area B΄: C.H. 1+100 – 1+900) of section 3.1 of the Egnatia Highway (Edafos Engineering Consultans S.A., 2003).

3.3 Investigation of the Drainage Gravel Piles application

According to the above we ascertain that, in this specific landslide, apart from many heterogeneous layers, the main manifestation mechanism of ground motions is related directly to the change of the additional, mostly, hydrostatic pressures and the hydrological conditions, as well as the gradient changes of landscaped slopes that cause flashing of water and lead to local or generalized failures. This was the pretext to investigate new types of drainage measures, the so-called **Drainage Gravel Piles**. These operate as the amount of water inserted in them, by the pierced landslide materials, is channeled into the river terrace which characterized by high permeability and this provide a satisfactory level of security against landslide.

The hydrogeological overview of the region is characterized by the supernatant drainage materials, of high water-bearing capacity but low permeability ($k \sim 2{,}0 \times 10^{-5}$cm/sec) and the shallow well horizon, because of the underlying flysch formations, the clay composition of which are responsible for the very slow (practically zero) rate of groundwater drainage in the buried river terrace. So, between the supernatant drainage materials and the impermeable flysch background, a distinctive slide surface is created. (Fig. B2).

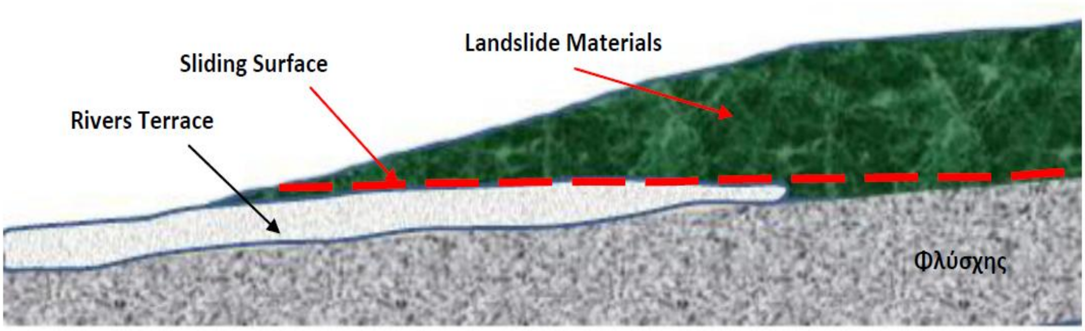


Figure B2: Hypothetical range of materials overlying landslide buried river terrace.

Based on the above assumption, the problem of dimensioning the drainage wells is basically reduced to the study of the change in flow of groundwater in an aquifer well, which is caused by the well function that reach the impervious background. The assessment of groundwater drawdown due to ongoing pumping tests is investigated, both in the wells, as well as in their surrounding area. For this reason, we represented schematically the level change caused by the pumping of the surface, in an unconfined underground aquifer (Fig. B3) and the level change caused by water channeling, in the underlying (buried) river terrace, in the case of Gravel Piles application in an area (Fig. B4).

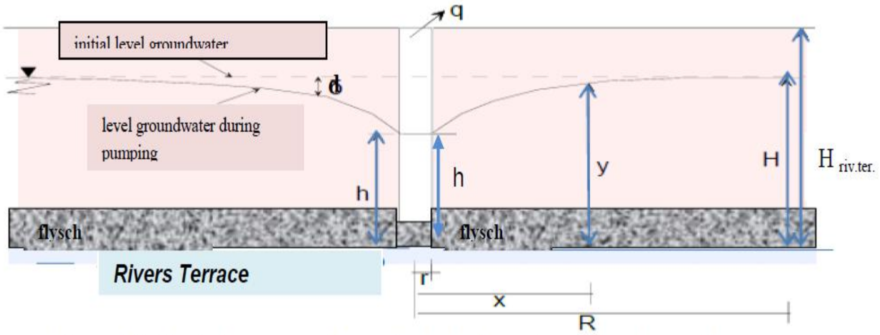


Figure B3: Typical case pumping well - level change in aquifer free surface

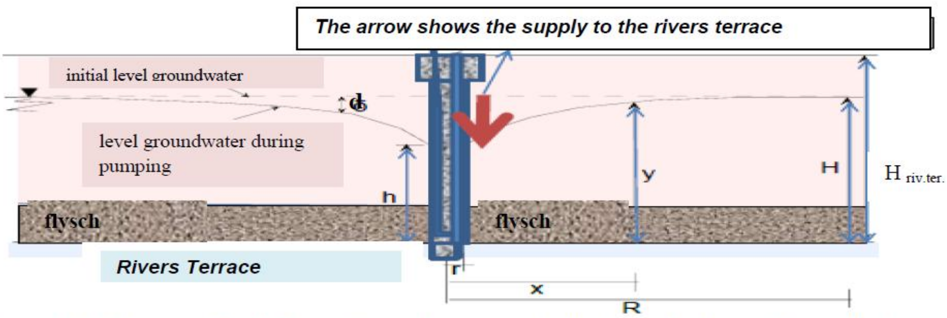


Figure B4: Schematic level change by applying gravel piles instead of pumping well - in aquifer free surface

Of these figures indicate the correlation of level change in both cases which are takes the shape of an inverted cone. In the second case, concerning the real under study problem, the pumping is regarded as groundwater channeling in the river terrace. Therefore, the pump supply is estimated based on gravel piles test runs, by channeling within them an amount of water of about 2,5m^3 and measuring its reduction rate.

The results of these tests can be used when the "quality" of the river terrace, on which the desired rate is mainly depended, is the same throughout the research area. Let us use for example 15΄ as an indicative average time required for the water drawdown in the gravel piles. The pump supply is consequently given the value **q = *2.5m^3 /15 X 60sec= 0.0028 m^3/sec.***

Due to the correlation of the two above cases the Thiem equations, of pumping tests, apply, so according to the symbolizations in Fig. B3 & B4, we get:

$$\mathbf{q = \frac{\pi k\,(H^2 - y^2)}{\ln (R/x)}} \qquad (2)$$

$$k = \frac{q}{\pi(H^2-h^2)} \ln \frac{R}{r} \qquad (3)$$

The level of the aquifer which is obtained during design is the level which corresponds to the most "wet" period of the year, so the rainwater supply is intentionally disregarded [5 & 10]. We therefore apply the known relations and laws of underground hydraulics, for the application of which the assumptions of paragraph 2.2 are endorsed and they should be satisfied by the actual hydrogeological conditions of the area. The recommended arrangement among the Gravel piles is the ***linear*** one, ***because***:

- The area is riverine, so the further we move away towards the interior of the slope the biggest the likelihood of non-detecting the terrace gets and penetration adequacy of the gravel piles is not provided in the underlying river terrace.
- Throughout the mass of the landslide materials there is a distinctive equable distribution of pore pressure, resulting in *the identification of the free surface of the permeable layer and the level of the river*.

Note that the drainage in a landslide area with failures in various posts, without their hydraulic communication, is achieved by applying groups of Drainage Gravel Piles in these sub-positions.

3.4 Calculation of the suitable distance between the Gravel Piles

For the investigation of the requisite arrangement of the drainage gravel piles, a good knowledge of geotechnical conditions, as well as hydraulic parameters of the landslide area is required. These data are obtained from executing sample drillings and by installing piezometers and inclinometers within them. The former is used for level measurements and their changes and the second for the certification of ground motions, as well as for the verification of their reduction, after the application of the drainage program, and therefore for the achievement of the goal of our study.

As mentioned above, the precise mathematical model of free surface flows is described by the Thiem equation (equation 1), with a series of assumptions. The solution of this equation, for a typical pumping case of a well in an aquifer, gives the following equations for the calculation of the supply and the change of free surface (in different forms and based on the symbolizations in Fig. B4):

$$\mathbf{q = \frac{\pi k\,(H^2 - y^2)}{\ln (R/x)}} \qquad (4)$$

$$\mathbf{q = \frac{\pi k\,(H^2 - h^2)}{\ln (R/r)}} \qquad (5)$$

$$\mathbf{q = \frac{\pi k\,(y^2 - h^2)}{\ln (x/r)}} \qquad (6)$$

From the equality of the two equations (5) and (6) => $\frac{\pi k\,(H^2 - h^2)}{\ln (R/r)} = \frac{\pi k\,(y^2 - h^2)}{\ln (R/r)}$ =>

$$\mathbf{y^2 = h^2 + \frac{H^2 - h^2}{\ln (R/r)} \ln(x/r)} \qquad (7)$$

where:
H = the initial level of the aquifer, before pumping,
h = the water level in the well, during pumping,
r = the distance from the centre of the well, in which the depth of the aquifer is equal to h and which coincides with the radius of the drainage well,
R = the impact radius of the well, i.e. the distance beyond which no drawdown due to pumping is observed,
x = the distance from the centre of the well, in which the depth of the aquifer is equal to y.

From equation (7) by solving for x we get the equation:

$$x = \exp\left(\ln \frac{R}{r} \times \frac{y^2 - h^2}{H^2 - h^2} + \ln r\right) \qquad (8)$$

The solution of equations 4-7 requires the estimation of sizes H, R and h. In point of the initial level H of the aquifer, before the pumping, it depends on the occurrence depth of the river terrace (= $\mathbf{H_{riv.ter.}}$). During designing, the initial level of the aquifer is measured, $\mathbf{H_{in.lev.}}$, so we get:

$H = H_{riv.ter.} - H_{in.lev.}$

Porchet after a lot of trials of pumping proposed, suggested the approximate, empirical relation ***ln (R/r) = 4.651*** (which also we use). It has also been estimated that there is a specific value for the water level h, h_{cruc}, beyond which it can no longer be reduced and it equals: ***$h_{cruc} \approx ⅓H \div ⅔ H = ½ H$.*** Thus solving equation (6) the q_{cruc}= … m^3/s is estimated. Also, for flow rates higher than q_{cruc}, and therefore for the actual pump supply as well, the value of h does not drop below h_{cruc}, hence the design value ***$h = h_{κριτ} = 0,5 X H$.*** [5] is accepted. The relegation by β m of the initial level of the aquifer is examined, so that under the drainage conditions created by the simultaneous operation of the gravel piles arrangements, proposed, to find itself below the level of the slide surface. A linear arrangement is selected, with α the axial distance of the gravel piles (Fig. B5). The distance x from the centers of the specific gravel piles equals x = a/2 => a **= 2x**.

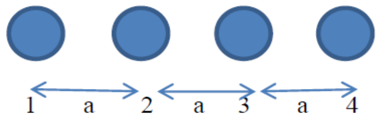


Figure B5: Order gravel piles fixed axial distance a

For the proper function of the gravel piles arrangement we set as a target that the final level value, at a random point inside the study zone, should come of the calculation of the overall drawdown at this point, due to their simultaneous function, that serves the objective of the slope stability. So, the goal of our study is reduced to the calculation of distance x and subsequently by equation (8), distance a [6 & 12]:

$$\boldsymbol{a=2x=2\exp\left(\ln \frac{R}{r} \times \frac{y^2-h^2}{H^2-h^2}+\ln r\right)} \qquad (9)$$

From results, of a georesearch program has preceded, we estimated the average occurrence of the river terrace: **$H_{riv.ter.}$ =25m** and the underground water level in the landslide materials: **$H_{in.lev.}$ =17m.** We also want the function of a single gravel pile to induce a drawdown equal to half the required value, that is d=b/2m and b= required level- $H_{in.lev.}$ and because of Fig. B4: y=H–d => y=H-d/2. The required level is related to the **occurrence depth of the slide surface** which occurs on the interfacial boundary of landslide materials-flysch background (i.e. **about 20 to 22m deep)**. Thereby, the minimum required level for the area stability should be in 22m deep, so:

$q=2,5m^3$ /sec (we put the inserted water amount during tests as the pump supply).

$H_{riv.ter.}$= 25m

$H_{in.lev.}$ = 17m => H = $H_{riv.ter.}$ – $H_{in.lev.}$= 25-17m = 8m

b=required level - $H_{in.lev.}$= 22m – 17m = 5m => d = b/2 = 2,5m, The following also apply:

ln R/r = 4.651 h = 0.5 x H = 0.5x 8m=4m και y = H- b/2 = 8 – 2,5m = 5,5m

r=d/2=1m/2=0.5m (we use the drill diameter, on ground surface)

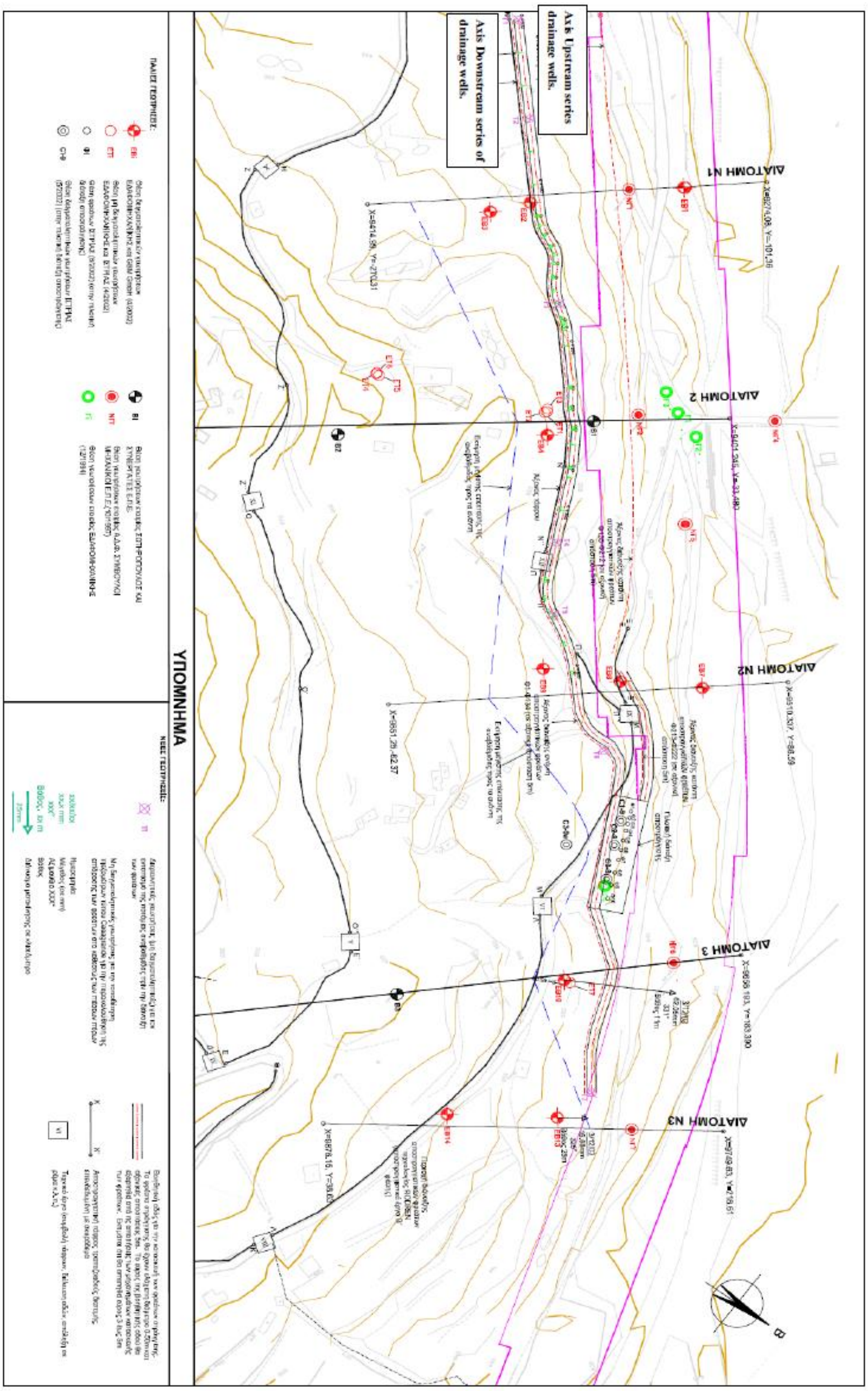
By applying then relationship (2), we get:

$$\boldsymbol{a = 2x=2\exp\left(\ln \frac{R}{r} \times \frac{y^2-h^2}{H^2-h^2}+\ln r\right) = 2\exp\left(4.651 \times \frac{5,52-42}{82-42}+\ln 0,5\right) = 2\exp 0,71=4,3m}$$

The required distance between the gravel piles is therefore ~4.5m.

3.5 Application of Drainage Gravel Piles

The general picture given by the measurements of the already installed instruments in the area confirmed that this is a slope of limit equilibrium. Amongst other measures proposed for the stabilization of the slope were also the deep drainage works, which concerned the drainage wells of the 1st and 2nd group (Drainage Gravel Piles). These permeate the landslide materials and reach down about 3 to 5m within the river terrace gravels. By monitoring and the estimating the optimal operating distance of the gravel piles, it was resulted and proposed that of 5.0 m. They are arranged into two rows, the downstream and the upstream row (Map A3). The upstream well row included wells Φ99 to Φ134, at axial distances, with very few exceptions, of about 5m. They are 33 in total (102&104 are missing) and they were drilled in 10th/2007. The upstream row included wells Φ135 to Φ217 and after a modification they were drilled one well at a time, so, in total 42 wells were drilled in 9th/2007. [4]



Map A3: Horizontiography of the landslide area (1+100 – 1+900) of the section 3.1 of the Egnatia Highway (Distinguished the drainage pilot program and axes opening of downstream and upstream wells series). (Egnatia Highway S.A. Measurement Department of the Geotechnical Instruments).

3.6 Effects of the Drainage Gravel Piles application on the landslide area

As part of our study, we monitored the progress of the landslide phenomenon through constant observation and evaluation of the measurements of the piezometers and inclinometers for many years (up to five years 3^{rd}/2012, since the deep drainage works construction). In this way, we investigated the success of the drainage project by monitoring the groundwater level, while, at the same time, we observed the reduction of ground motions and consequently the stabilization of the greater landslide area. More specifically, from the evaluation of these measurements- some tables are given indicatively in annex D- we ascertain that ***after the completion of the project a drawdown is observed and this drawdown trend goes on throughout the whole observation period***. Thus therefore, observing the measurements of the installed piezometers (ET4, ET5, ET6, ET7), in the greater landslide area B, from 2002 up to their last measurement 3^{rd}/2012, we observe humiliation of level. This drawdown ranges from a minimum decrease of 1m (ET4) up to the maximum decrease of 8.43m (ET5) or an up to 96% decrease, after the Drainage Gravel Piles construction (9^{th}/2007). There are of course intermediate values of drawdown e.g. a 2.9m decrease (ET6), or a 1.82m decrease (ET7), (**Table D1**).

Table D1: Measurements level of ET-piezometers in the area of the landslide.

	Days	Depth instrument (m)	Water level from ground	Level reduction after the wells	Remarks
ET4 (Days installation 18/4/02)	22/10/02	6	5,20	**0,80**	Dry
	13/3/12		Dry		
ET5 (Days installation 18/4/02)	10/9/02	13	4,57	**8,43**	Dry
	13/3/12		Dry		
ET6 (Days installation 24/4/02)	9/6/05	21	16,52	**2,91**	* Blocked in 21m
	13/3/12		19,43		
ET7 (Days installation 24/4/02)	10/9/02	13	2,20	**1,82**	
	15/2/11		4,02		

After the construction of the Gravel Piles, previously installed piezometers in the area also exhibit a drawdown (EB2, EB3, EB5, EB6, EB9, EB12 & EB13), with minimal reduction of 0.14m (EB2) and maximum reduction of 3.11m (EB2). Intermediate reductions of approximate 2.59m (EB3) and 0.87m (EB5) are also observed. We stress out the greatest drawdowns concern the piezometers closest to wells area, while it is worth noting that though the level may not be reduced enough, it never reaches, however, its initial price, not even in winter or the rainy spring months (March-April), e.g. piezometer EB3. Also the levels of the two row wells of deep drainage works remain stable at low prices even in winter months, on all these years. From the measurements of pore pressures we obtained from the Casagrande piezometers, we notice, in the downstream wells NΠ15 and NΠ17 and upstream wells NΠ6-2 NΠ6-3, ***reductions in pore pressures in depths greater than 10m*** (depth of interest), from ***a minimum of 6% (NΠ17) up to a maximum of 21% (NΠ15),*** (**Table D2**).

Table D2: Measurements of NII-Casagrande piezometers in the area of the landslide.

NΠ6-2 Days installation 5/10/06 - Depth instrument 19,50m.		NΠ15 Days installation 11/10/06 - Depth instrument 23m.	
Days	**kPa**	**Days**	**kPa**
1/3/2007	117,692	13/7/2007	100,607
24/9/2007	112,230	24/9/2007	91,148
14/12/2007	109,929	24/4/2009	86,370
13/3/2012	109,796	16/2/2011	Destroyed
NΠ6-3 Days installation 5/10/06 – Depth instrument 29,50m.		**NΠ17 Days installation 04/10/06 - Depth instrument 22m.**	
Days	**kPa**	**Days**	**kPa**
1/3/2007	80,870	13/7/2007	133,240
24/9/2007	66,726	24/9/2007	128,791
14/12/2007	69,053	13/3/2012	128,083
13/3/2012	69,713		

Finally, **in Table D3**, we see characteristically some of the installed inclinometers of the deep drainage project area. We observe a reduction in ground motions after the deep drainage project construction. The inclinometers that did not display any motion or distortion prior to the construction of the wells, such as ***EB8 & EB9, continued to show the same behavior after their construction***. On the contrary, in the inclinometers of the drills (***EB3, EB10, EB11 and EB13***) that ***had recorded motions before the drainage gravel piles construction, a significant decrease, tending to zero, was noted after their construction***. More specifically: the motion rate ***completely stopped in inclinometer EB11***, in inclinometer ***EB3 the motion decreased from 7mm per year to 0.80mm per year*** and in inclinometer ***EB13 from 20-25mm per year to 7.3mm per year***. The ***EB10*** inclinometer ***was destroyed*** (on 06.08.2004) due to heavy distortions and was replaced by ***EB10N, and the motion decreased from ~ 21mm per year to 7.5mm per year***. Regarding the newest inclinometers which are mounted in the drills in the upstream wells area NK1, NK2, NK4 & NK6 ***we observed motion only in the NK***, with an observed ***move decrease from 1.71mm per year to 0.46mm per year***.

Table D3: Speed movement and maximum movements derived from measurements of inclinometer in the area of the landslide.

inclinometer	Depth motion (m)	Moving speed (mm/month) Days installation-10/07	Moving speed (mm/month) 10/07-03/12	Maximum movement (mm)	Remarks
EB 3	3,0-5,00	0,00-0,94 (M.O. 7mm/year)	0,01-0,41 (M.O. 0,8mm/year)	**7,75**	
EB 10	11,00	0,06-13,75	**Maximum movement 89,76 mm** (destroyed 6/04 and replaced by EB10N).		
EB 10N	11,00	0,05-1,57 (M.O. 21mm/year)	0,18-0,92 (M.O. 7,57mm/year)	**41,05**	
EB 11	30,00	0,00-1,60	**Maximum movement 8,35mm** (until 14/5/07, Since there is no development of the phenomenon).		
EB 13	25,00	0,34- (-4,75) (M.O. 20-25mm/year)	0,13-3,39 (M.O. 7,30 mm/year)	**Maximum movement 71,24mm** (until 15/4/09, Since there is no development of the phenomenon).	
NK6	22,00	0,00-0,80 (M.O. 1,71 mm/year)	0,00-0,12 (M.O. 0,46mm/year)	9,42	
EB 8	2,00-4,00	0,04	After 8/12/06 destroyed due asphalt paving.		
EB 9	25,00-35,00	**Strong deformations until 20/11/2004,** thereafter showed no particular development.			

From the monitoring and the evaluation of the measurements of the geotechnical instruments, for many years, confirm the success of this project. Namely, the construction of two rows of drainage wells (Drainage Gravel Piles) manage to drain the landslide materials within the river terrace materials, resulting in drawdown or immersion of the aquifer and the rate decrease of ground motions, thus the beginning of the stabilization of the landslide area.

IV. CONCLUSIONS

Finally, we conclusively report that:

- ***The drainage gravel piles, whether of minor range or of an extensive landslide***, in the presence of high water-bearing capacity within its structuring materials in cases of underlying unsaturated permeable body (e.g. buried river terrace), ***achieve the drainage of landslide materials in this permeable background, through the groundwater drawdown, the reduction of pore pressure and the consequential reduction of ground motions, therefore the beginning of landslide stabilization***.
- The drainage gravel piles achieve a ***greater groundwater drawdown or reduction of pore pressure, within the mass of the landslide materials, as the distance between the wells decreases and as the depth increases in the mass of the landslide materials***.
- ***The drainage of landslide areas***, in which failures are pointed out in various posts without their hydraulic communication, ***is achieved by applying groups of drainage gravel piles***.
- ***Finally, the study and application of the Drainage Gravel Piles*** in the abovementioned area of Egnatia Odos ***certify that these projects may not be sufficient on their own to entirely stop in time the motion of the landslide*** which occupies a large area and manifests recurrent landslide incidents, ***they contribute however to a greater extent than others to the stabilization of the situation and to further restoration of the equilibrium***.

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