Design of sustainable olive mill wastewaters ponds

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Abstract

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The geomembrane market for waterproofing ground ponds used to isolate olive mill wastewaters offers a wide choice both in terms of the material used and liner thickness and size. With regard to the physical and mechanical properties of the material forming the geomembrane, this paper proposes a method for the assessment and design of the waterproofing system. This method foresees the calculation and analysis of geomembrane stress caused by the most stressful conditions, also taking into consideration the physical characteristics of the material within the pond, the elastic and elastic-plastic behaviour of the geomembrane and the physical characteristics of the soil. Criteria and graphs for the rapid dimensioning of the waterproofing system are also proposed. In addition to the environmental and climatic characteristics of the site, the results presented also take into consideration the dimensional characteristics of the ponds and the physical properties of the olive mill wastewaters.

Keywords: agrifood waste; geomembrane liner; oil; LDPE liner; waterproof

In most cases, the majority of processing and transformation processes of agricultural products foresee the disposal of vast quantities of olive mill wastewaters, a situation which necessitates the creation of temporary accumulation and containment systems which are reliable and at the same time economical (Sinclair 2001). The creation of simple ponds, waterproofed by using special geomembranes made from polymeric materials is without doubt the most economical and, in some cases, the most rational solution (Bouazza 2002), above all regarding the need to obtain systems endowed with high accumulation capacities as well as the opportunity of locating such accumulations close to cultivated areas in order to encourage the agronomic reutilisation of the same olive mill wastewaters. The creation of ponds for the disposal of agro-industrial wastes generally consists of a truncated pyramid-shaped excavation in the ground, with slope angles varying from 15° to 45°, corresponding to a ratio between pond depth and horizontal distance between the base and summit of the slope varying between 1/3 and 2/3, a value linked to the soil internal friction angle of the pond. Waterproofing is usually carried with a plastic geomembrane after levelling the soil at the base and walls of the pond with a 20 cm lining of clay (Fig. 1). In recent years the geomembrane market has introduced a wide range of products, mainly used in the waterproofing of landfills and/or ponds. These products are above all composed of thermoplastic polymers including:

– polypropylene (PP),
– polyvinyl chloride (PVC),
– high-density polyethylene (HDPE),
– low-density polyethylene (LDPE).

In addition to the above-mentioned single-layer membranes, various types of geomembranes recently appeared on the market consisting of a combination of different materials which offer enhanced performance. One such example is membrane strengthened with geotextile, where the combina-

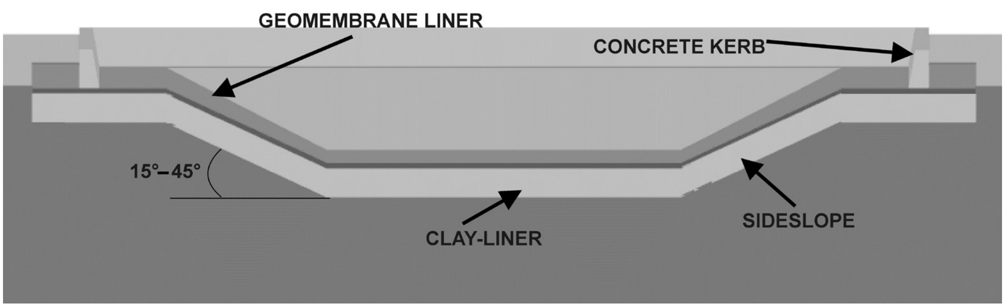

Fig. 1. Cross-section of a waterproofed pond

tion of plastic polymer with a reinforcing material results in a waterproofing membrane highly tear and puncture resistant which is also efficient in stabilising highly inclined slopes.

MATERIAL AND METHODS

The choice of the most suitable material for the waterproofing of ponds for olive mill wastewaters disposal requires a specific hierarchical analysis. A specific multi-criteria analysis was conducted by the authors (Fichera, Barreca 2004) in a previous paper which allowed a comparison and evaluation to be made of a number of categories of specific demands including: eco-compatibility, physical and mechanical properties and ease of on-site installation. The final result of the multi-criteria analysis is shown below (Fig. 2).

On the basis of the characteristics considered and analysed and in relation to the relative importance assigned to each, it emerged that the low-density polyethylene membrane (LDPE) was slightly more suitable (Pennington et al. 2004). With regard to the range of geomembrane liner stresses in olive mill wastewaters ponds, the present paper proposed and developed a method for the dimensioning and design of the waterproofing system. Specifically, the following factors were taken into consideration with regard to the use of LDPE geomembrane: stress caused by its own weight, wind, thermal variations and stress-strain behaviour of the liner caused by solid residues of olive mill wastewaters.

The phases of the method proposed may be summarised as follows (Fig. 3):

(1.) Identification of the construction site and the characteristics of the geomembrane clay liners, selected from the geometric characteristics of the pond including: capacity, sideslopes, max. depth, planimetric dimensions, physical-chemical characteristics of the olive mill wastewaters.

(2.) Calculation of the min. thickness of the LDPE geomembrane resistant to stress-strain and calculation of the min. water level necessary at the bottom of the pond to prevent wind uplift.

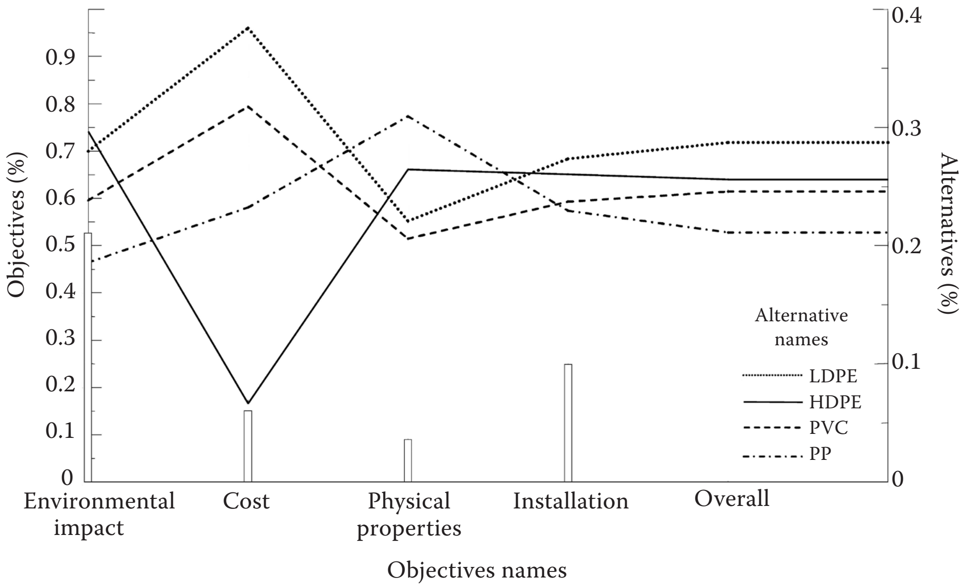

Fig. 2. Final classification of scores obtained by each geomembrane

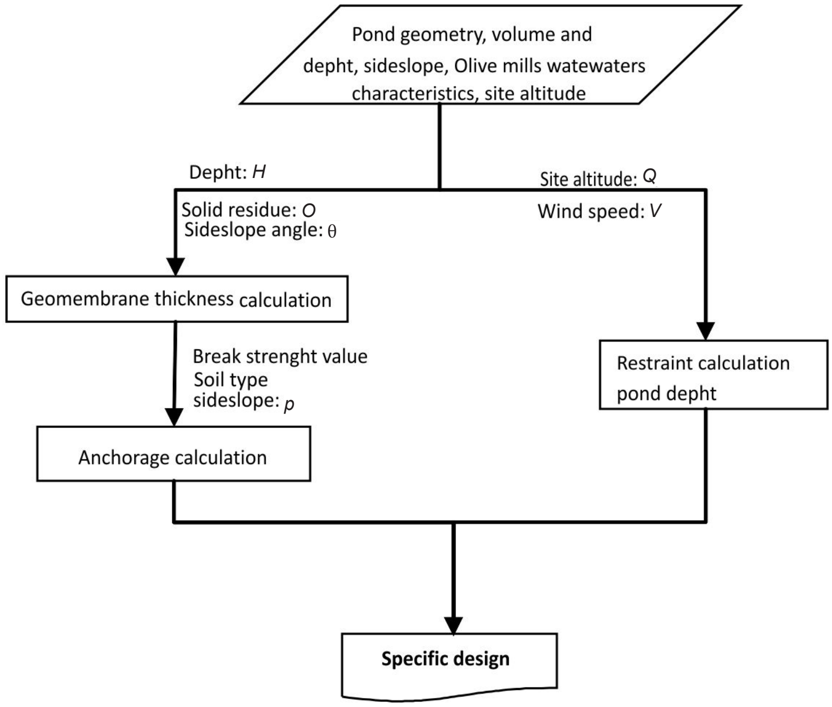

Fig. 3. Flow chart for the design of the pond waterproofing system

(3.) Calculation of anchorage at the edge of the pond as a function of calculated LDPE film thickness and tear resistance.
(4.) Development of detailed design adopting the values obtained in the previous phases.

RESULTS AND DISCUSSION

When full, the hydrostatic force of the liquid in the pond occurs perpendicularly to the walls without causing particular stress to the geomembrane. However, when empty, solid matter and olive cake residues in olive mill wastewaters may result in geomembrane failure as a result of tensile and shear stresses (Reddy, Boris 1999; Hsieh, Hsieh 2003). The present paper, taking into account the method of analysis of stresses by finite elements on geomembranes (Kodikara 2000), applies a specific model of analysis which considers the elasticity of the geomembrane-clay interface system to develop a graph for the rapid calculation of min. geomembrane thickness. This model can simulate the elastic behaviour of the geomembrane and the elastic-plastic behaviour of the geomembrane-clay interface (Sharma, Lewis 1994), obtaining with greater precision compared to the limit equilibrium method, actual stress within the geomembrane itself. In particular, with reference to a small geomembrane element, it is possible to express the differential equations of elastic deformations as:

$$\frac{dT(x)}{dx} = \tau_l - \tau_u \qquad (1)$$

$$\frac{du}{dx} = \frac{T}{t \times E} \qquad (2)$$

$$\frac{d^2u}{dx^2} = \frac{1}{t \times E}(\tau_l - \tau_u) \qquad (3)$$

where:
$T(x)$ – tensile tension in the geomembrane at distance x from the anchorage (kN/m)
τ_l, τ_u – shear stress at the lower and upper side of the geomembrane at distance x from the anchorage caused by the solid matter layer of olive mill wastewaters (Pa)
E – Young's modulus of the geomembrane (Pa)
u – elastic displacement of the geomembrane at distance x from the anchorage (m)
t – thickness of the geomembrane (m)

The vertical and horizontal stress on the geomembrane caused by the deposited layer of solid residues may be expressed as follows:

$$\sigma_v = (O + x\sin\theta - x\cos\theta\tan\beta)\gamma \qquad (4)$$

$$\sigma_h = K_x \times \sigma_v \qquad (5)$$

where:
O – thickness of the layer of olive mill wastewaters solid residues (m)

γ – unit weight of the layer of olive mill wastewaters solid residues (N/m^3)
θ – angle to the horizontal level of the sideslope (°)
β – slope angle of the solid residue layer (°)
K_x – ratio between the horizontal and vertical stresses of the solid residue layer

With reference to the Mhor-Coulomb criteria, the normal and shear stress components on the geomembrane may be expressed as follows:

$$\sigma_n = \sigma_v \sin^2\theta + \sigma_h \cos^2\theta = (K_x \cos^2\theta + \sin^2\theta) \times \times (O + x\sin^2\theta - x\cos\theta\tan\beta)\gamma \quad (6)$$

$$\tau_u = 1/2(\sigma_v - \sigma_h)\sin2\theta = 1/2(1 - K_x) \times \times (O + x\sin\theta - x\text{con}\theta\tan\beta)\gamma\sin2\theta \quad (7)$$

In the event that displacement u is lower than the peak value u_p which represents the point between the elastic and plastic trend of the geomembrane-clay interface (Vaid, Rinne 1995), then the differential equation of displacement is expressed as:

$$\frac{d^2u}{dx^2} - \frac{k_s}{tE}u = -\frac{\gamma\sin2\theta}{2tE}(1-K_x)(O + x\sin\theta - x\cos\theta\tan\beta) \quad (8)$$

where:
$k_s = G/D$
G – shear modulus of the clay liner
D – thickness of the clay layer

In the event of the value of u_p being exceeded, the geomembrane exhibits a plastic behaviour which may be expressed by the following relationship:

$$\tau_l = \eta\tau_l^p = \eta[\sigma_n - p_l)\tan j_1 + c_1] \quad (9)$$

and therefore the differential second grade displacement equation may be expressed as:

$$\frac{d^2u}{dx^2} = \frac{1}{tE}\left\{\begin{array}{l}\eta\left[\left(K_x\cos^2\theta + \sin^2\theta\right)A\gamma - p_l\right]\tan\varphi_l \\ +\eta c_l - \frac{1}{2}\left(1-K_x\right)A\gamma\sin2\theta\end{array}\right\} \quad (10)$$

where:
$A = (H + x\sin\theta - x\cos\theta\tan\beta)$
τ_l, τ_u – shear stress at the lower and upper side of the geomembrane at distance x from the anchorage caused by the solid matter layer of olive mill wastewaters (Pa)
p_l – liquid pressure below the geomembrane (Pa)
σ_n – normal stress on the membrane at distance x from the anchorage (Pa)
σ_{max} – max. permissible normal stress on the membrane (Pa)
φ_l – friction angle at the lower interface of the geomembrane (°)
c_l – adhesion coefficient at the geomembrane-clay interface (–)
η – ratio of residual peak shear strength of the geomembrane-clay interface

In order to solve Eqs (8) and (10) it is necessary to establish the boundary conditions applicable to the problem: for $x = 0$, $u = 0$ and for $x = L$, $T = 0$ where L equals geomembrane length on the slope. Mean numeric values of the physical and mechanical characteristics of widely available LDPE geomembranes and those of olive mill wastewaters were attributed to the coefficients of the above-mentioned equations, thus: $\gamma = 12{,}400\ N/m^3$, $E_{LDPE} = 180$ MPa, $\sigma_{max} = 2.485$ MPa, (break strength = 24.85 MPa) $k_s = 50$ MPa/m, $D = 0.20$ m, $G = 10$ MPa, $K_x = 0.50$, $\eta = 1$, $p_l = 0$ (absence of water below the geomembrane), $\phi_1 = 5°$, $c_1 = 0$. These equations were solved with a developed iterative computational method through a spreadsheet which provided a series of results for θ varying between 15° and 45° and 5 and 10 cm for residual layer height. From the sequence of values obtained it is possible to graph the following curves for the dimensioning of the min. thickness of the geomembrane (Fig. 4).

The wind and, in particular, the variation of local atmospheric pressure associated with it, creates uplift on the geomembrane which is especially significant on the sideslopes and bottom of the pond (Zornberg, Giroud 1997). A particular restraint is required to prevent uplift (Giroud et al. 1995), which could result in the geomembrane tearing and/or displacement. It is therefore necessary to ensure a min. permanent liquid storage even during periods when the pond is not used to prevent uplift of the waterproofing membrane. With regard to the above, a previous paper by the same authors (Fichera, Barreca 2004) developed criteria for calculating the min. depth of water to use as a restraint. The following graph allows direct calculation of the min. water depth value h, as a function of the max. wind speed and altitude of the area under consideration (Fig. 5).

In order to prevent suction-induced geomembrane uplift or downdrag caused by its own weight it is necessary to design a suitable geomembrane anchoring

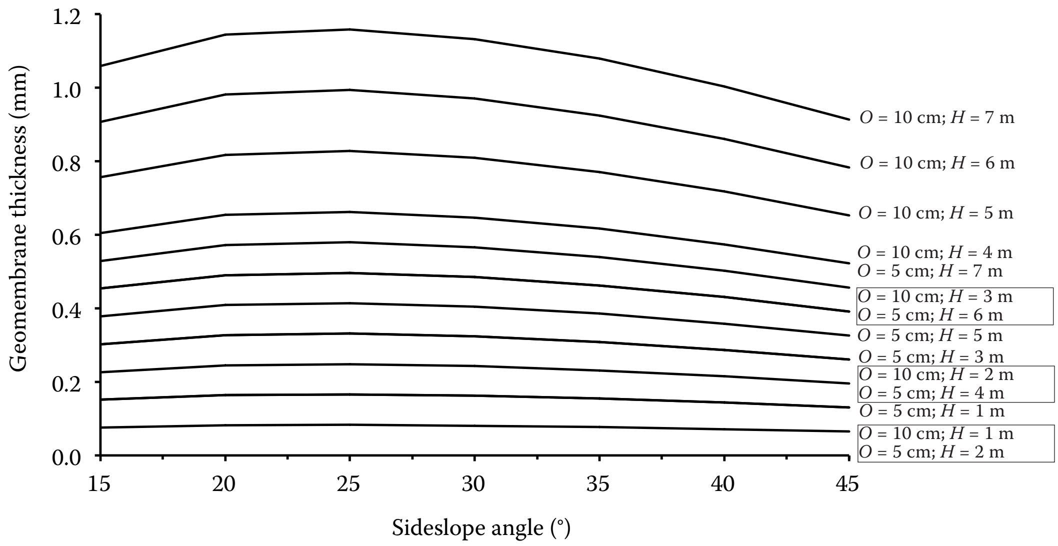

Fig. 4. Establishing min. thickness of the LDPE geomembrane
Q – thickness of the layer of olive mill waste water solid residue; H – depht of pond

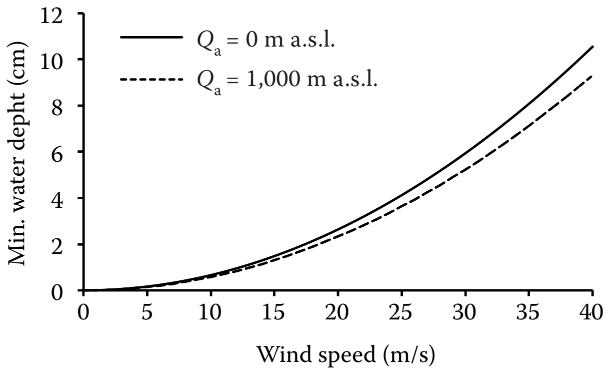

Fig. 5. Min. filling depth as a function of wind speed and altitude
Q_a – altitude above the sea

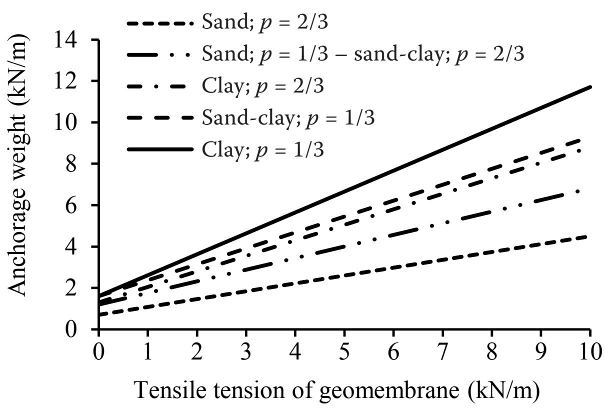

Fig. 6. Vertical anchoring weight as a function of LDPE geomembrane tensile tension value, soil type and sideslope
p – slope ratio

(Giroud et al. 1999) system at the edge of the pond. The anchoring system proposed in the present paper for olive mill wastewaters ponds envisages simply placing a number of concrete kerbs above the edge which, as well as acting as a restraint, creates an effective protective barrier against the accidental falling of soil or loose material from the edge into the pond; moreover they facilitate the quick installation and removal of the geomembrane. The graph in Fig. 6 provides a user-friendly application of the method. Intercepting the line of soil characteristics and slope inclination with the geomembrane break-strength value divided by safety factor on the x-axis gives the anchoring kerb weight along the y-axis which represents the max. anchoring force which allows release of the geomembrane before breaking.

The waterproofing of olive mill wastewaters ponds poses a series of complex problems requiring careful analysis and assessment. This paper proposes a method for designing a waterproofing system which, thanks to the use of specific graphs provides a useful tool for the easy and rapid dimensioning of the geomembrane and anchoring and restraint systems of the waterproofing which overcomes a number of computational difficulties linked to the solution of particularly complex numeric equations. The creation of the above graphs took into account a number of characteristic parameters of LDPE geomembranes and the standard chemical-physical characteristics of olive mill wastewaters. However, these can be varied to modify and adapt the graphs to different scenarios and productive contexts.

CONCLUSION

The creation of simple ponds, waterproofed by using plastic films is without doubt the most rational solution, above all regarding the need to obtain systems endowed with high accumulation capacities as well as the opportunity of locating such accumulations close to cultivated areas in order to encourage the agronomic reutilisation of the same olive mill wastewaters (Altieri, Esposito 2010). It therefore becomes fundamental to provide personnel and operators in the sector with user-friendly tools which enable them to design and create reliable and efficient systems that are also economically sustainable (Sinclair 2001; Rebitzer et al. 2004). The importance of this problem is also felt by businesses that produce and market waterproofing geomembranes for disposal sites with the result that various solutions to minimise installation and the overall cost of realization are being studied such as the creation of pre-formed and seamed waterproof geomembranes to place directly within the excavation which guarantees the greatest resistance to leakage and infiltration. With regard to the range of geomembrane liner stresses in olive mill wastewaters ponds, the present paper proposed and developed a method for the dimensioning and design of the waterproofing system and has attempted to develop and establish such tools by providing graphs for a rapid and easy dimensioning of the main elements of the waterproofing system.

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