Journal of Hazardous Materials 162 (2009) 1–9

Contents lists available at ScienceDirect

Journal of Hazardous Materials

journal homepage: www.elsevier.com/locate/jhazmat

Review

Environmental risk index: A tool to assess the safety of dams for leachate

Francisco J. Colomer Mendoza*, Antonio Gallardo Izquierdo

Department of Mechanical Engineering and Construction, Universitat Jaume I, Av. de Vicente Sos Baynat s/n, 12071 Castellón, Spain

ARTICLE INFO

Article history:
Received 15 May 2007
Received in revised form 26 March 2008
Accepted 5 May 2008
Available online 9 May 2008

Keywords:
Dam for leachate
Environmental risk
Constructive characteristics of the dam
Pollution load
Rating curves

ABSTRACT

Dams for leachate store very toxic substances that contain a large amount of organic material and, probably, heavy metals; they therefore constitute an important threat to the environment. Existing models of environmental risk assessment for landfills do not take into consideration the specific risk that leachate dams may represent for the environment. In this paper a methodology to improve the environmental safety is presented according to the parameters used in their construction and management. In order to do that, the following characteristics of the dam must be known: (1) geotechnical stability, (2) erosion of downstream slope, (3) type of sealing of the dam, (4) overtopping probability, (5) volume of leachate stored inside the dam and (6) pollution load of leachate. Once these parameters have been calculated, they are transformed by means of rating curves into homogeneous units, so as to make it possible to operate between them. From the study and analysis of these parameters an environmental risk index for a dam for leachate can be calculated. If the environmental risk index exceeds an established value then it involves a dam for leachate with high environmental risk, therefore preventive measures in its design, construction and management would be necessary.

Contents

* Corresponding author. Tel.: +34 964728111; fax: +34 964728106.
E-mail address: fcolomer@emc.uji.es (F.J. Colomer Mendoza).

0304-3894/$ – see front matter © 2008 Elsevier B.V. All rights reserved.
doi:10.1016/j.jhazmat.2008.05.018

1. Introduction

There are different types of dangerous liquids such as the leachate from landfills and composting plants, municipal wastewater and industrial wastewater which are often stored in earth dams and, therefore, present a considerable environmental risk.

The liquids stored in dams or deposits contain a great amount of polluting substances and compounds, including organic and inorganic chemical substances and heavy metals [1–3]. In fact, leachates can involve the main source of pollution on groundwater and surface water [4–7].

If one of these dams breaks, the liquid would pour out forming an avalanche that would advance along the line of maximum slope of the land, which would cause an important environmental impact. So, it is necessary a maximum precaution in their construction and management.

Dams for toxic liquids, particularly for leachates, in Spain were observed by orthophotography and their location was analysed. Results showed that 20% of them are located less than 2000 m from a river, lake or water stream. If a dam breaks leachate would be led downstream to reach that water body [8]. Moreover, in the surrounding areas of the leachate dam different environmental elements could exist which would also be affected by the leachate. Therefore it is necessary to assess the environmental risk that leachate dams generate so as to be able to calculate the potential environmental impact associated to them.

Generally speaking, in order to determine and quantify the environmental risk of a dam for leachates, the dimensions of environmental damage and the frequency of the event have to be considered [9]. Taking these criteria into account, several different methodologies have been developed to assess environmental risk by organisations such as the U.S. Environmental Protection Agency [10,11], the World Health Organization [12–14], the New Zealand Landcare Research [15] and the Spanish Normalisation and Certification Agency [16,17]. All of them calculate the environmental risk from the multiplication between the probability that an event occurs by the gravity of the consequences.

In addition to the general methodologies for environmental risk assessment, there are other specific methodologies based on deterministic models that are designed to determine migrations of pollutant liquids or gases from the source to the receivers, through different paths [18–27]. The more restrictions are introduced, the more complicated these models become. In the end they may be so complex that results can be a long way from reflecting the real situation. Nevertheless, environmental risk assessment, as a method of analysis, is an effective tool to protect the environment in the presence of risks generated by a composting plant or landfill [28].

The computer models used to assess environmental risk in landfills are limited to assessing the risks deriving from leachate and from the biogas generated by wastes [29–31]. Therefore, the environmental risk caused by the storage of toxic liquids in a dam or deposit is not considered. Due to the weakness of the described methodologies in this research, an alternative model is designed to valuate specifically the environmental risk of the leachate dams.

This method would permit to assess the environmental risk without the need to gather historical data of accidents or subjective and ambiguous scenarios, which is necessary in traditional methods.

2. Materials and methods

Most of the leachate dams existing in Spain are constructed with compacted earth sealed with geomembrane [8]. The parameters which define the structural safety and the stability of a dam are the geotechnical stability of the dam's slopes, the erosion of the downstream slope, the type of sealing and the probability of overtopping due to intense rainfall. From the environmental point of view, the parameters that can influence risk are the volume of stored toxic liquid and its pollution load.

The methodology for calculating the environmental risk of a leachate dam described in this paper is based on the parameters which define the structural safety and characteristics of the dam. The values of these parameters are measured in different units and therefore, once the values have been calculated, they have to be transformed into homogeneous units (Fig. 1). To do so, a group of Spanish technicians were chosen and asked to trace the rating curve for each parameter. The rating curves relate the heterogeneous units of each parameter of safety on dams with the units of the environmental risk index (ERI). They are the average rating curves supplied by technicians.

Furthermore, the group of technicians were asked to rate the weight of each parameter according to the environmental risk generated by each of them. The value of environmental risk index of the dam parameters (ERI DP) can be calculated by combining the values of environmental risk and the weight of each parameter.

2.1. Geotechnical stability of the slopes

A properly geotechnical stability in slopes constructed with earth is necessary in order to guarantee the lack of slides. The geotechnical stability of a slope is known by means of the safety factor (SF). The schematic procedure for calculating this value is shown in Fig. 2. In order to calculate the slope SF it is necessary to know: the geometric properties of the dam (downstream slope, upstream slope and height); mechanical properties of the material (effective cohesion, effective friction angle and density); and the seismic coefficient of the region. The methods most commonly used to calculate slope stability are analytical methods [32–38] or computer programs. Most of the different regulations about dam design that have been studied are mainly concerned with earth dams and reservoirs for water storage and require an SF value between 1.0 and 2.0 [39–42]. A value of SF > 1.4 is recommended.

2.2. Erosion of downstream slope

Intense rainfalls can provoke loss of materials in earth slopes due to erosion. If the loss material has a high value, the stability of the slope can diminish. In order to calculate the value corresponding to the loss of soil due to erosion (A [t/ha year][1]) the universal soil loss equation (USLE) is used (Fig. 3). Eq. (1) is recommended for international purposes [43]. The USLE equation provides techniques for numerically evaluating effects of climate (rainfall factor), soil properties (erosion soil factor) topography (length of the embankment factor), crop-productivity level (crop factor), time and method of seeding, crop sequence, residue management and special conservation practices (cultivation of the soil factor), and other pertinent variables that effect soil erosion.

$$A = R \cdot K \cdot L \cdot S \cdot C \cdot P \tag{1}$$

where R is the rain factor (J cm/m^2 h); K the soil erosionability factor (t m^2 h/ha J cm); L the slope length factor (dimensionless); S the slope factor (dimensionless); C the crop factor (dimensionless); P is the soil conservation practice factor (dimensionless).

[1] ha: hectare = 10,000 m^2 = 2471 acres.

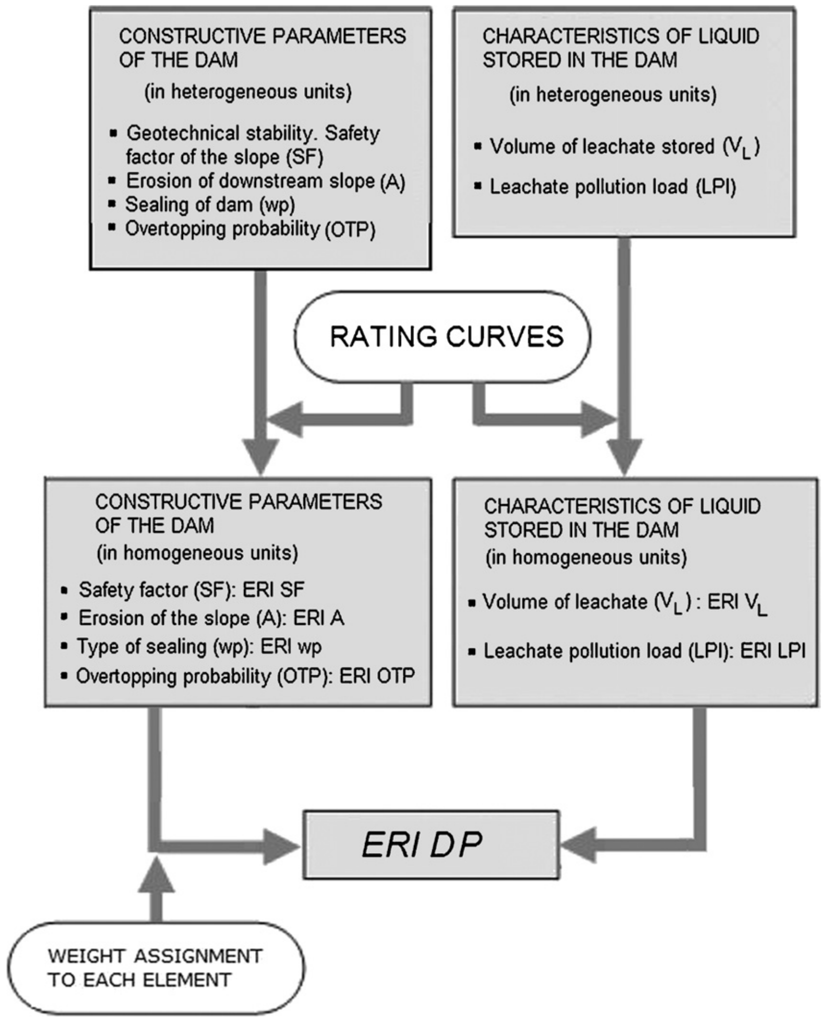

Fig. 1. Parameters and steps to elaborate ERI DP.

2.3. Sealing of dam

An adequate sealing of an earth dam is necessary to avoid seepage, leakage and its consequent piping which could cause the collapse of the embankment. When a leachate dam is being constructed, different rules and regulations have to be applied according to the country in which it is being built in. For example, in Spain leachate dams have to be sealed in a similar way to a solid waste landfill, that is to say, using a compacted clay liner and a synthetic geomembrane. Thus, a permeability coefficient $K \leq 10^{-9}$ m/s is guaranteed [44].

The materials most commonly used to waterproof landfills and leachate dams are high density polyethylene (HDPE), polyvinyl chloride (PVC), chlorosulphonated polyethylene (CSPE) and chlo-

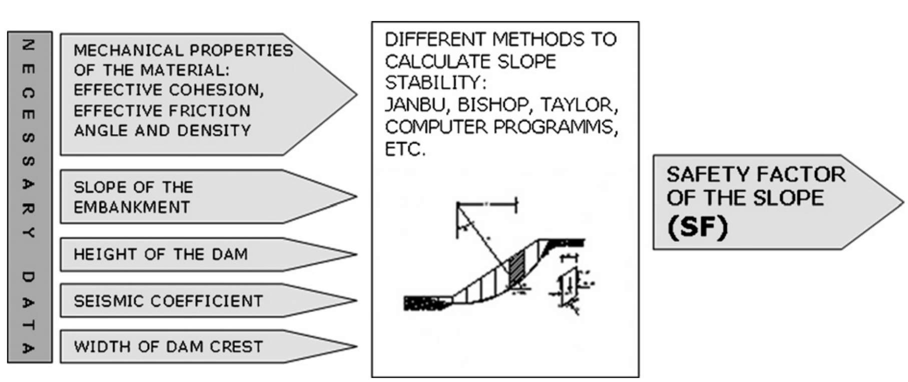

Fig. 2. Parameters to calculate SF.

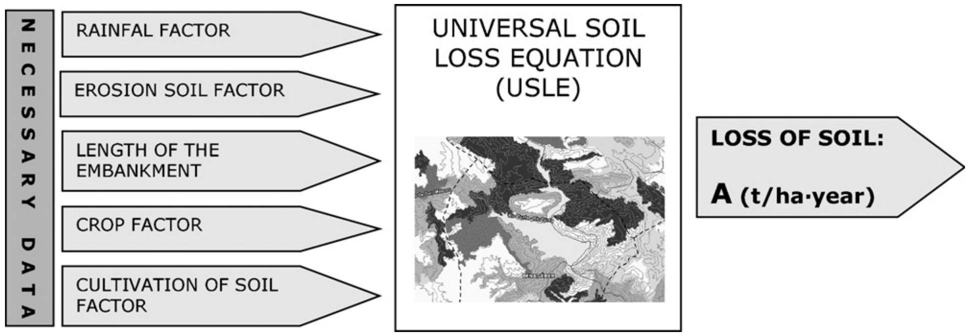

Fig. 3. Parameters to calculate A.

rine polyethylene (CPE). The thickness of these geomembranes can vary from 0.5 mm to 3 mm, although a thickness above 1.5 mm is recommended [44–49].

According to the different systems employed, four types of sealing were defined. A value from 1 to 4 was assigned according to the increasing safety of the sealing system (wp). In the worst type (type 1; wp = 1) no sealing system is installed and the liquid is poured directly onto the soil until it percolates into the subsoil or is drained by artificial methods. The second type (type 2; wp = 2) involves a dam sealed with a compacted clay liner with low permeability. The third type, (type 3; wp = 3) the most widespread system, use a compacted clay liner that is separated from a synthetic geomembrane by geotextile. In the fourth type (type 4; wp = 4), besides the compacted clay and geomembrane liner, a drainage liner is also installed between the geotextile and compacted clay.

2.4. Overtopping probability

Capacity of the earth dams have to be calculated according to meteorological data and above all, precipitation data. If this parameter is not correctly calculated, intense rainfalls can fill the dam and provoke overtopping which would erode the slopes, diminishing their stability. In order to calculate the probability of overtopping due to intense rainfall it is necessary to know the data represented in Fig. 4. The data concerning 1-in-100 year 24-h period return rainfall can be obtained from the closest meteorological station. The geometric data (top surface of the dam, surface which pours into the dam and capacity of defence) are stated in the project of dam. The resulting value *T*(%) represents the probability of a rainfall that exceeds the storage capacity of the dam.

2.5. Volume of leachate storage inside the dam

The environmental impact that leachate can cause depends directly on the volume of leachate stored in the dam and on its pollution load. To obtain the volume data, an average of the maximum volume contained, in normal conditions, in the dam (m^3) has to be calculated.

2.6. Leachate pollution load

The pollution load of leachate is measured by means of analytical data of the liquid which include organic compounds, inorganic compounds and heavy metals. The higher be the pollution load, the higher be the environmental risk. The analytical method established by Kumar and Alappat [50] was applied in order to obtain the pollution load of the leachate. This method proposes a leachate pollution index (LPI) from the composition and characteristics of the leachate. It need data from the organic compounds, inorganic compounds and heavy metals and by means of rating curves get a value of LPI. Necessary data are shown in Fig. 5.

2.7. Rating curves

Following the calculation described in the previous items, the next step consists in generating the rating curves from the constructive characteristics of the leachate dam, the safety factor of the outer slope (SF), loss of soil due to erosion (*A*; t/ha year), type of sealing used in the dam and the probability of overtopping (OTP; %). Each parameter is measured using different units and therefore they cannot be operated together. The resulting units are cited as environmental risk index units (ERI) and six rating curves are required to perform this conversion. The ERI values of each parameter vary from 0 to 1.

To calculate these rating curves a representative group of Spanish technicians was asked, by means of a questionnaire, to draw up the statistical correlation between the dam safety factor and the environmental risk index. These technicians were researchers and scientists working on soil stability and mechanics, experts from construction companies, engineering companies, civil servants, etc. According to a statistical data (Statistical Spanish Institute), an average number of 3000–3500 persons are working or studying themes relating to this purpose.

Because of the difficulty to get surveys, an error level of 10% is tolerated and 95% of confidence level has been chosen for the result. A total of 243 mails were sent out to people responsible for the design, control, monitoring and management of landfills. As

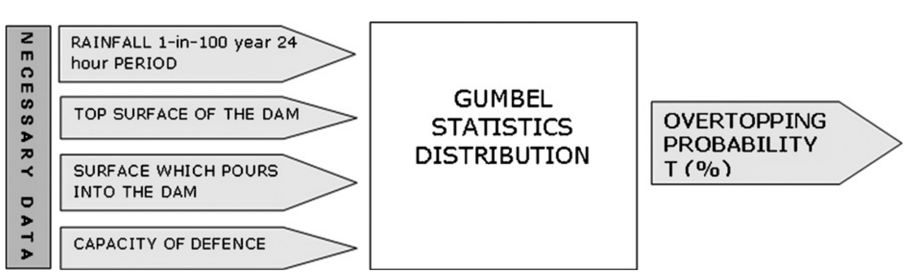

Fig. 4. Parameters to calculate T(%).

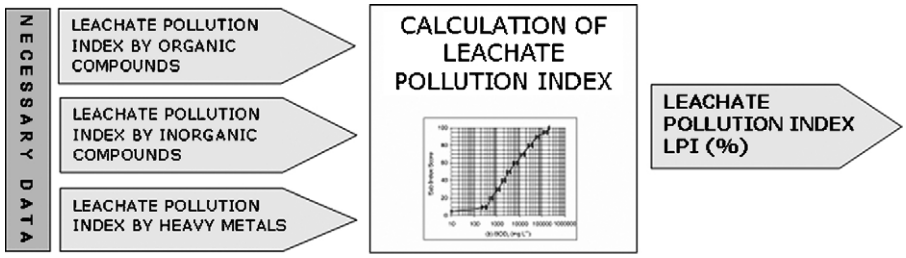

Fig. 5. Parameters to calculate LPI(%).

Table 1
Distribution of sent and received polls asking rating curves

	Received polls	Sent polls
Polls sent by professors at universities	43	95
Polls sent by engineers of private offices	27	78
Polls sent by civil servants from the Spanish Ministry of the Environment	17	58
Polls sent by individual engineers	6	12
Total	93	243

Table 2
Distribution of sent and received polls asking weight factors

	Received polls	Sent polls
Polls sent by professors at universities	45	95
Polls sent by engineers of private offices	27	78
Polls sent by civil servants from the Spanish Ministry of the Environment	18	58
Polls sent by individual engineers	9	12
Total	99	243

shown in Table 1, 93 correctly completed polls were received which can be acceptable according to the error level tolerated.

When the questionnaires had been collected, they were grouped. Different points were taken to build regression model (a sample is showed in Fig. 6). A statistical analysis was performed in order to investigate whether the results were statistically significant and whether they could be used in the IRA equation. The computer program Statgraphics Plus 5.1. was utilised to do this.

2.8. Weight factors

In order to assign the weight to each leachate dam safety parameter, a second questionnaire was sent out to collect information from the group of technicians. These technicians were researchers and scientists working on soil stability and mechanics, experts from construction companies, engineering companies, civil servants, etc.

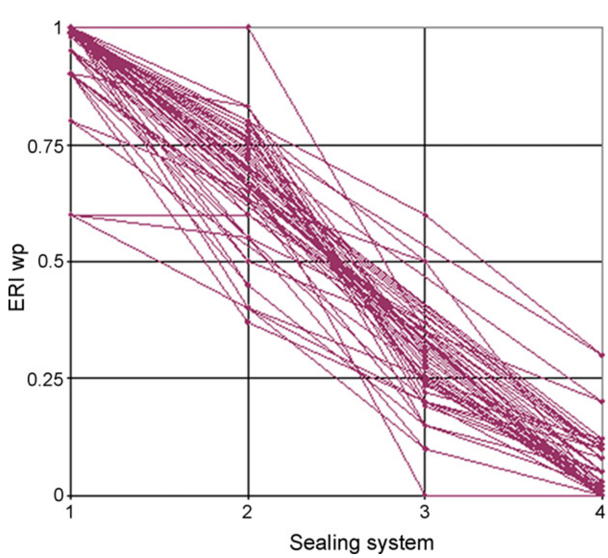

Fig. 6. Received polls asking the rating curve of sealing system.

According to a statistical data, an average number of 3000–3500 persons are working or studying themes relating with this purpose.

Because of the difficulty to get surveys an error level of 10% is tolerated and 95% of confidence level has been chosen for the result. A total of 243 mails were sent out to people responsible for the design, control, monitoring and management of landfills. As shown in Table 2, 99 correctly completed polls were received which can be acceptable according to the error level tolerated.

3. Results and discussion

3.1. Safety factor of the downstream slope

The approved value for the SF which indicates a safe dam is considered to be above 1.4. From these data, the rating curve of the ERI SF (environmental risk index of the safety factor) was calculated. The regression analysis calculated from the linear model of the data obtained by the questionnaires has the following values:

Correlation coefficient = −0.95.
$R^2 = 90.36$.
P-value < 0.01.

The adjusted linear model equation is:

$$\text{ERI SF} = 0.9522 - 0.3680\text{SF} \quad (2)$$

Because the P-value in the ANOVA table is lower than 0.01, there is a statistically significant relation between the ERI SF and downstream slope SF with a confidence level of 99%. The graph with the values from the statistical treatment and the regression line are shown in Fig. 7. The R^2 statistic indicates that the model explains 90.36% of the variability in the ERI SF. The correlation coefficient is equal to −0.95, which indicates a relatively strong relation between the variables.

3.2. Loss of soil due to erosion

The soil material which is lost because of erosion depends on the rainfall data for the region, the morphology of the dam and geolog-

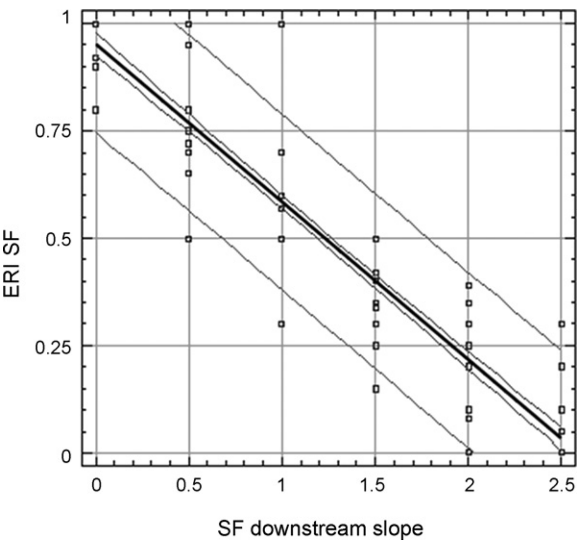

Fig. 7. Rating curve of SF.

ical properties of the earth. The regression analysis calculated from the linear model of the data obtained by the questionnaire has the following values:

Correlation coefficient = 0.79.
R^2 = 62.01.
P-value < 0.01.

The adjusted linear model equation is:

$$\text{ERI A} = 0.0597 + 0.0087A \quad (3)$$

Because the *P*-value in the ANOVA table is lower than 0.01, there is a statistically significant relation between ERI *A* and eroded material with a confidence level of 99%. The graph with the values from the statistical treatment and the regression line are shown in Fig. 8. The R^2 statistic indicates that the model explains 62.01% of the variability in ERI *A*. The correlation coefficient is equal to 0.79, which indicates a relatively strong relation between the variables.

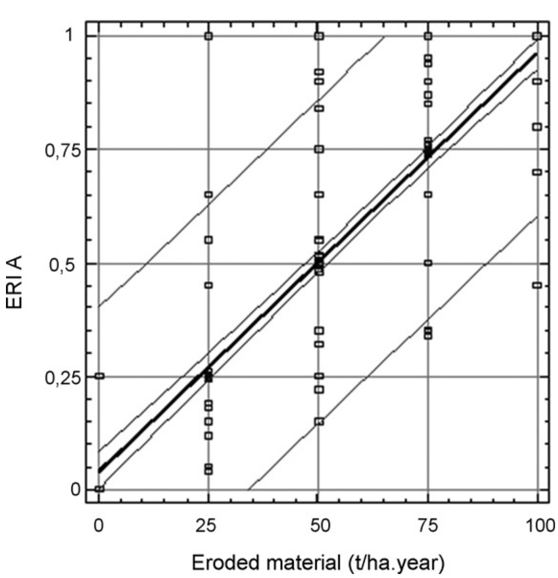

Fig. 8. rating curve of eroded material.

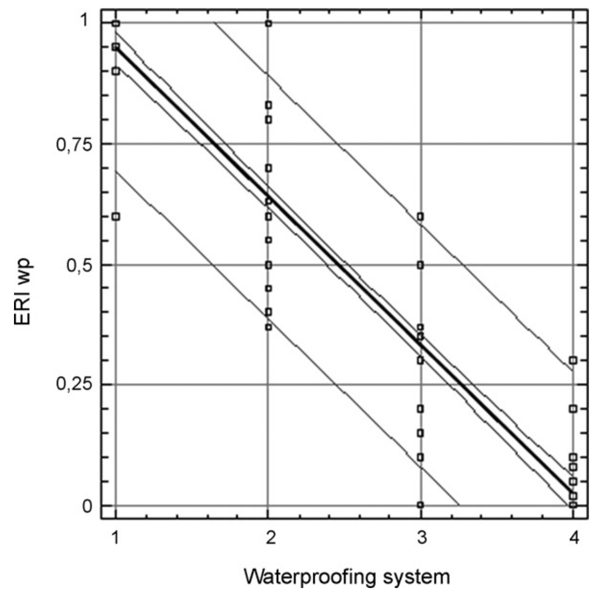

Fig. 9. Rating curve of waterproofing system.

3.3. Sealing system

The regression analysis calculated from the linear model of the data obtained by means of the questionnaire about the sealing system has the following values:

Correlation coefficient = −0.94.
R^2 = 88.15.
P-value < 0.01.

The adjusted linear model equation is:

$$\text{ERI wp} = 1.2537 - 0.3076\text{wp} \quad (4)$$

Because the *P*-value in the ANOVA table is lower than 0.01, there is a statistically significant relation between ERI *A* and eroded material with a confidence level of 99%. The graph with the values from the statistical treatment and the regression line are shown in Fig. 9. The R^2 statistic indicates that the model explains 88.15% of the variability in ERI wp. The correlation coefficient is equal to −0.94, which indicates a relatively strong relation between the variables.

3.4. Overtopping probability

The overtopping probability (OTP) can be calculated from knowing the capacity of the dam and the maximum annual rainfall in a 24-h period. The probability that the amount of rainfall exceeds the capacity of the dam can be found from the overtopping probability environmental risk index (ERI OTP). So when the OTP is 100%, then the ERI OTP is equal to 1. If the OTP is 0%, then the ERI OTP is equal to 0. The regression analysis calculated from the linear model of the data obtained by the questionnaire about the probability of overtopping has the following values:

Correlation coefficient = 0.87.
R^2 = 75.01.
P-value < 0.01.

The adjusted linear model equation is:

$$\text{ERI OTP} = 0.0336 + 0.0095\text{OTP} \quad (5)$$

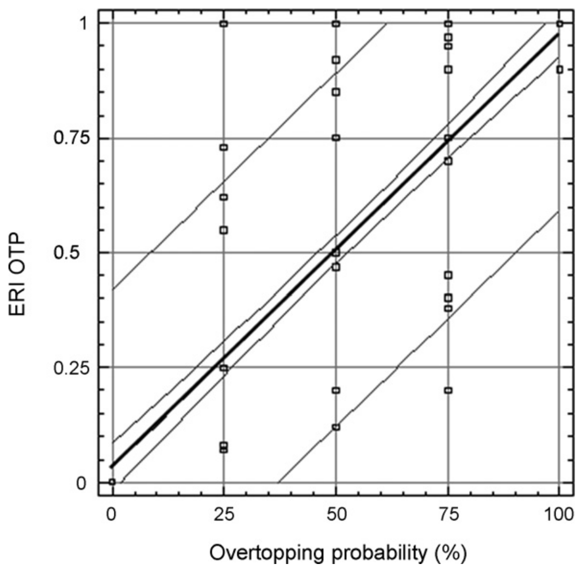

Fig. 10. Rating curve of overtopping probability.

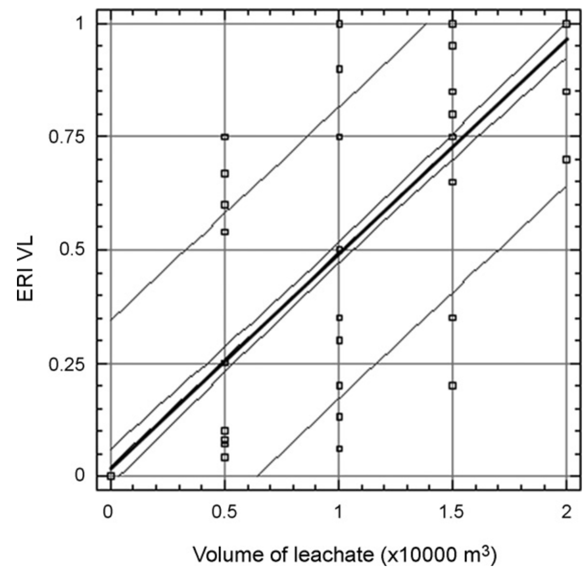

Fig. 11. Rating curve of volume of leachate.

Because the *P*-value in the ANOVA table is lower than 0.01, there is a statistically significant relation between ERI OTP and the overtopping probability with a confidence level of 99%. The graph with the values from the statistical treatment and the regression line are shown in Fig. 10. The R^2 statistic indicates that the model explains 75.01% of the variability in ERI OTP. The correlation coefficient is equal to 0.87, which indicates a relatively strong relation between the variables.

3.5. Volume of leachate stored in the dam

The bigger the volume stored in the dam (V_L), the bigger the environmental risk (ERI V_L) will be because, in the case of dambreak, the flow released will be more harmful. The regression analysis calculated from the linear model of the data obtained by means of the questionnaire about volume of leachate stored in the dam has the following values:

Correlation coefficient = 0.90.
R^2 = 80.90.
P-value < 0.01.

The adjusted linear model equation is:

$$\text{ERI}\, V_L = 0.0210 + 0.00005 V_L \quad (6)$$

Because the *P*-value in the ANOVA table is lower than 0.01, there is a statistically significant relation between ERI V_L and volume of leachate with a confidence level of 99%. The graph with the values from the statistical treatment and the regression line are shown in Fig. 11. The R^2 statistic indicates that the model explains 80.90% of the variability in ERI V_L. The correlation coefficient is equal to 0.90, which indicates a relatively strong relation between the variables.

3.6. Leachate pollution index (LPI%)

When the LPI has been calculated it is necessary to transform it into ERI units. The regression analysis calculated from the linear model of the data obtained by means of the questionnaire about volume of leachate stored in the dam has the following values:

Correlation coefficient = 0.94.
R^2 = 87.87.
P-value < 0.01.

The adjusted linear model equation is:

$$\text{ERI LPI} = 0.04359 + 0.0097\text{LPI\%} \quad (7)$$

Because the *P*-value in the ANOVA table is lower than 0.01, there is a statistically significant relation between ERI LPI and LPI with a confidence level of 99%. The graph with the values from the statistical treatment and the regression line are shown in Fig. 12. The R^2 statistic indicates that the model explains 87.87% of the variability in ERI LPI. The correlation coefficient is equal to 0.94, which indicates a relatively strong relation between the variables.

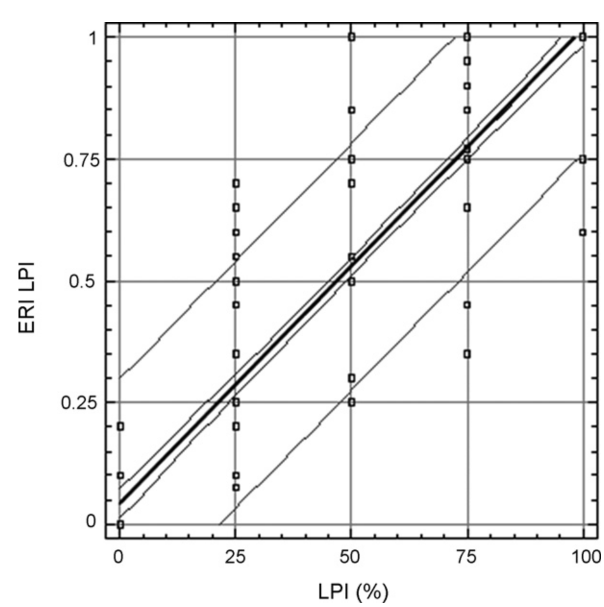

Fig. 12. Rating curve of LPI.

Table 3
Weight factor of each ERI

Safety parameter	$(\bar{x}_i)$	s	VC (%)	wf (weight)
ERI SF: safety factor of the downstream slope	3.824	1.143	30	0.260
ERI *A*: loss of material due to erosion	3.167	1.505	48	0.214
ERI wp: waterproofing of the dam	4.556	0.634	14	0.308
ERI OTP: probability of overtopping due to intense rainfall	3.222	1.176	36	0.218
Total $(\sum_{i=1}^{4}\bar{x_i})$	14.769			1.000

Table 4
Results of ERI DP in different dams from different landfills

	SF	*A*	wp	OTP	V_L	LPI(%)	ERI DP
Rejects landfill [1]	3.51	26.03	3	0.22	13,600	29,386	0.037
Composting plant [1]	5.17	165.40	3	7.55	22,000	28,703	0.109
Non-hazardous wastes landfill	2.08	438.70	3	0.98	14,000	37,316	0.103
MSW landfill [1]	1.88	77.41	3	9.44	27,000	34,655	0.134
MSW landfill [2]	2.50	34.50	3	6.05	10,000	40,211	0.044
Composting plant [2]	1.75	100.39	3	10.01	25,000	22,354	0.107
Toxic wastes landfill	2.88	33.34	4	1.25	15,000	68,351	0.047
Rejects landfill [2]	1.41	45.30	3	11.21	9,000	31,661	0.054

3.7. Weight factors

The technicians were asked to evaluate from 1 to 5, from lesser to higher importance, each parameter of the leachate dam according to its influence on the safety of the dam and, therefore, its influence on the risk associated to the leachate dam. The summary of the results from the data analysis is represented in Table 3 with the mean average (x), standard deviation (s) and variation coefficient (VC). The value with biggest relative dispersion is the loss of soil, which reveals a large degree of variability between the data provided by the panel of technicians. The sealing of the dam, however, displays little variability, which shows a large degree of heterogeneity between data obtained from the group of technicians.

To calculate the weight factor of each of the dam safety parameters, the arithmetical summa of the importance values $(\sum_{i=1}^{4}\bar{x_i})$ have to be calculated, and then the mean value of each parameter $(\bar{x}_i)$ must be divided between the sum of every parameter. So, $\sum_{i=1}^{4}\mathrm{wf}_i = 1$

$$\mathrm{wf}_i = \frac{\bar{x}_i}{\sum_{i=1}^{4}x_i} \quad (8)$$

3.8. Equation of risk generated by a leachate dam

The ERI resulting from the leachate dam safety parameters depends on all the factors described previously, i.e. the safety factor of the slope, loss of material by erosion, sealing system, probability of overtopping due to intense rainfall, volume of leachate stored in the dam and the leachate pollution index.

By applying rating curves the units of every parameter can be turned into homogeneous units and, therefore, ERI units can be obtained, that is to say, ERI SF, ERI *A*, ERI wp, ERI OTP, ERI V_L and ERI LPI. The values of the first four environmental risk units are multiplied by their weight factor and they are then added because each of them is independent of the others. The sum is multiplied ERI V_L times and ERI LPI times to get the overall influence on the environmental risk. The resulting equation is:

$$\mathrm{ERI\,DP} = (0.260\mathrm{ERI\,SF} + 0.214\mathrm{ERI}\,A + 0.308\mathrm{ERI\,wp} + 0.218\mathrm{ERI\,OTP})\mathrm{ERI}\,V_L\mathrm{ERI\,LPI} \quad (9)$$

The values of ERI DP belong to the interval [0,1]. The bigger ERI DP is, the higher the environmental risk generated by the leachate dam will be.

3.9. Applications

The methodology described here has been applied to 8 cases of different existing leachate dams in Spain (Table 4). These are eight leachate dams which are located in eight different types of facilities: landfill of rejects (2 cases), composting plant (2 cases), non-hazardous wastes landfill (1 case), municipal solid waste landfill (2 cases) and toxic wastes landfill (1 case).

Eight cases correspond to leachate dams in use, and no accidents have been registered in over 5 years' operation. The calculated values of ERI DP are below 0.14.

The ERI DP methodology has been validated by means of these eight real cases which enables to define the threshold value below which a leachate dam can be considered as safe from the environmental point of view. This value can be set at 0.15. Nevertheless, to make the sample representative, a larger number of real applications have to be calculated.

4. Conclusions

The safety of a leachate dam depends on different parameters related to the morphology and structure of the dam. These parameters are the safety factor of the downstream slope (SF), loss of material due to erosion (*A*), the sealing system (wp), the probability of overtopping due to intense rainfall (OTP), the volume of leachate stored in the dam (V_L) and the polluting load of the leachate (LPI).

The units of each parameter are different and therefore it is not possible to operate between them. To do so, it is necessary to use rating curves, which homogenise the units to environmental risk index units (ERI) according to the parameter: ERI SF, ERI *A*, ERI wp, ERI OTP, ERI V_L, and ERI LPI.

Because not every parameter has the same importance or weight as regards safety, a weight is assigned to each parameter.

The different parameters, measured in homogeneous units with their corresponding weight, are combined with one another in order to elaborate the environmental risk index for the dam parameters equation (ERI DP). The equation represents the sum of each parameter by its weight. The environmental risk is directly proportional to the risk generated by the volume of leachate stored and the pollution load of the leachate; therefore, ERI V_L and ERI LPI have to be multiplied by the previous sum.

From the above mentioned equation it can be observed that if the dam stores water for irrigation, the ERI would be void. This is not completely true because, if a dambreak occurs, the avalanche generated by a large amount of water would cause an important environmental impact. However, this sort of dam does not usually contain a large volume of liquid and therefore the risk generated by a potential avalanche is not taken into account, and the environmental risk is limited to the polluting liquids.

In the cases analysed, the methodology is validated and a value for the environmental risk index can be established. Values lower than the established value indicates a safe dam. According to calculations from eight cases, a value equal to 0.11 can be proposed as a safe value for the ERI.

Notwithstanding, a qualitative analysis is necessary to take a decision because if only one of the parameters of the dam has a very dangerous value, can be sufficient to avoid the construction of the dam. So, there are parameters difficult to prevent (erosion and pollution load) therefore, if these parameters have a high value of environmental risk, the value of ERI DP have to be reduced by means of increasing the capacity of the dam (therefore, the OTP would be reduced), increasing the SF value (>1.4) or improving the sealing system (geomembrane and drainage liner).

References

[1] L. Koshy, E. Paris, S. Ling, T. Jones, K. BéruBé, Bioreactivity of leachate from municipal solid waste landfills—assessment of toxicity, Sci. Total Environ. 384 (2007) 171–181.

[2] J.D. Arneth, G. Milde, H. Kerndorff, R. Schleyer, Waste deposit influences on groundwater quality as a tool for waste type and site selection for final storage quality, in: P. Baccini (Ed.), The Landfill, vol. 20, Springer, Berlin, 1989, pp. 399–424 (Lecture Notes in Earth Sciences).

[3] T.H. Christensen, P. Kjeldsen, P.L. Bjerg, D.L. Jensen, J.B. Christensen, H.B. Albrechtsen, G. Heron, Biogeochemistry of landfill leachate plumes, Appl. Geochem. 16 (2001) 659–718.

[4] A. Ding, Z. Zhang, J. Fu, L. Cheng, Biological control of leachate from municipal landfills, Chemosphere 44 (2001) 1–8.

[5] P. Flyhammar, Estimation of heavy metal information in municipal solid waste, Sci. Total Environ. 198 (1997) 123–133.

[6] J.S. Hancock, I.R. Phillips, M. Seignor, Fate of contaminants deriving from municipal solid wastes in saturated landfills, in: Proceedings Sardinia 95, 5th International Landfill Symposium, vol. 3, 1995, pp. 611–620.

[7] M. Isidori, M. Lavorgna, A. Nardelli, A. Parrella, Toxicity identification evaluation of leachates from municipal solid waste landfills: a multispecies approach, Chemosphere 52 (2003) 85–94.

[8] F.J. Colomer, Thesis: Análisis y sistematización de la seguridad medioambiental de los vertederos de residuos urbanos y asimilables. Aplicación a las balsas de lixiviados. Universidad Politécnica de Valencia, Valencia, 2006.

[9] P. Dopazo, Coordinación y gerencia de riesgos ambientales (responsabilidad civil por daños ambientales y seguro ambiental), Observatorio Medioambiental. 5 (2002) 103–125.

[10] U.S.EPA, Guidance or risk characterization, Science Policy Council, U.S. Environmental Protection Agency, Washington, DC, 1995.

[11] U.S.EPA, Guidance on Cumulative Risk Assessment, Science Policy Council, U.S. Environmental Protection Agency, Washington, DC, 1997.

[12] G. Suter, T. Vermeire, W. Munns, J. Sekizawa, Framework for the Integration of Health and Ecological Risk Assessment, vol. II, World Health Organization, Geneva, 2001.

[13] G. Suter, T. Vermeire, W. Munns, J. Sekizawa, An integrated framework for health and ecological risk assessment, Toxicol. Appl. Pharm. 207 (2005) s2611–s2616.

[14] WHO, Additional types of integration in risk assessment, World Health Organization, UNEP, ILO, Geneva, WHO/IPCS/IRA/01/02, 2001.

[15] LCR, Risk Assessment for Contaminated Sites in New Zealand, Landcare Research, Wellington, 2003.

[16] AENOR, Análisis y evaluación del riesgo medioambiental. Asociación Española de Normalización y Certificación, Madrid, UNE 150008 EX, 2000, pp. 1–33.

[17] PERM, Evaluación de riesgos medioambientales. Pool Español de Riesgos Medioambientales. Entidad reaseguradora de riesgos de contaminación, www.perm.es, Madrid, 2005.

[18] G. Attenborough, D. Hall, R.G. Gregory, L. McGoochan, Development of a landfill gas risk assessment model: Gassim, 2002, http://www.lqm.co.uk/free/GasSim%20SWANA%202002.pdf.

[19] M. Blumberga, R. Thunvik, Thesis: Risk Assessment of the Skede landfill in Liepaja, Latvia, Stockholm, 2001, http://www.lwr.kth.se/Publikationer/PDF_Files/AMOV_EX_2001_4.pdf.

[20] J. Bradley, Guidance on assessment of risk from landfill sites, Environment Agency, Bristol, Bureau of Reclamation, 1980, Manual de Tierras, Bellisco, Madrid, 2004.

[21] F. Calvo, B. Moreno, M. Zamorano, M. Szanto, Environmental diagnosis methodology for municipal waste landfills, Waste Manage. 25 (2005) 768–779.

[22] F. Calvo, M. Zamorano, B. Moreno, Metodología de diagnóstico ambiental de vertederos como herramienta en la planificación ambiental. Colegio de Ing. de C.,C. y P. de Madrid, 2002, pp. 965–975.

[23] Golder Associates (NZ) Ltd., Risk assessment for small landfill closure criteria, Waste Management Institute New Zealand Incorporated, Ministry for the Environment, Christchurch, NZ. Application 4176, 2002, http://www.mfe.govt.nz/publications/waste/small-landfill-closure-dec02.pdf.

[24] A. Mavropoulos, Landfill Design Using Simplified Risk Assessment Procedures, WIT Press, EPEM SA, Greece, 2004.

[25] MFE, Risk Screened System, Ministry for the Environment, Wellington, NZ, 2004, http://www.mfe.govt.nz/publications/hazardous/contaminated-land-mgmt-guidelines-no3/contaminated-land-mgmt-guidelines-no3.pdf.

[26] D. Rapti-Caputo, F. Sdao, S. Masi, Pollution risk assessment based on hydrogeological data and management, Eng. Geol. 85 (2006) 111–121.

[27] SEPA, Framework for risk assessment for landfill sites. The geological barrier, mineral layer and the leachate sealing and drainage system, Scottish Environment Protection Agency, 2002, pp. 1–13, http://www.sepa.org.uk/pdf/guidance/landfill_directive/risk_assessment.pdf.

[28] T.E. Butt, K.O.K. Oduyemi, A holistic approach to concentration assessment of hazards in the risk assessment of landfill leachate, Environ. Int. 28 (2003) 597–608.

[29] Golder Associates, 2007, LandSim: http://www.landsim.co.uk/.

[30] Golder Associates, 2007, GasSim: http://www.gassim.co.uk/.

[31] EPA, Landfill Gas Emissions Model (LandGEM) Version 3.02 User's Guide, United States Environmental Protection Agency, EPA-600/R-05/047, 2005, http://www.epa.gov/ttncatc1/dir1/landgem-v302-guide.pdf.

[32] D.W. Taylor, Fundamentals of Soils Mechanics, Wiley, New York, 1948.

[33] A.W. Bishop, N. Morgenstern, Stability Coefficients for Earth Slopes, Geotechnique, vol. 10, Institution of Civil Engineers, London, 1960, pp. 129–150.

[34] J.H. Hunter, R.L. Schuster, Stability of Simple Cuttings in Normally Consolidated Clays, Geotechnique, vol. 18, Institution of Civil Engineers, Great Britain, 1968, pp. 372–378.

[35] Janbu, Nilmar, Discussion of paper Dimensionless Parameters for Homogeneous Earth Slopes by Bell, J. Soil Mech. Found. Div. ASCE 93 (1967) 367–374.

[36] N. Morgenstern, Stability Charts for Earth Slopes During Rapid Drawdown, Geotechnique, vol. 13, Institution of Civil Engineers, London, 1963, pp. 121–131.

[37] E. Spencer, A Method of Analysis of the Stability of Embankments Assuming Parallel Inter-Slice Forces, Geotechnique, vol. 17, Institution of Civil Engineers, London, 1967, pp. 11–26.

[38] K. Terzagui, R.B. Peck, Soil Mechanics in Engineering Practice, John Willey and Sons, Nueva York, 1967.

[39] Bureau of Reclamation, Manual de Tierras, Bellisco, Madrid, 1980.

[40] DEQ Land Quality, Solid Waste Landfill Guidance Document, Department of Environmental Quality, DEQ. 750 Front Street NE, Suite 120 Salem, OR 97310, 1998, http://www.deq.state.or.us/lq/sw/disposal/landfillguidance.htm.

[41] T.W. Lambe, R.V. Whitman, Mecánica de suelos, New edition, Limusa, Mexico, 1990.

[42] U.S. Department of Agriculture Soil Conservation Service Engineering Division, Earth Dams and Reservoirs, Technical Release, vol. 60, 1985, http://www.mde.state.md.us/assets/document/damsafety/NRCS/.

[43] W.H. Wischmeier, D.D. Smith, Predicting rainfall erosion losses, A guide to conservation planning, Agricultural Handbook No. 537, Sci. and Educ. Admin., U.S. Dept. Agr. Washington, DC, 1978, http://topsoil.nserl.purdue.edu/usle/AH_537.pdf.

[44] U.S.EPA, Solid Waste Disposal Facility Criteria Technical Manual, Office of Solid Waste and Emergency Response (5305), U.S. Environmental Protection Agency, Washington, DC, 1998, http://www.epa.gov/garbage/landfill/techman/intro.pdf.

[45] G.R. Koerner, R.M. Koerner, J.P. Martin, Design of landfill leachate-collection filters, J. Geotech. Eng. ASCE 120 (1994) 1792–1803.

[46] R.M. Koerner, Designing with Geosynthetics, 2nd edition, Prentice-Hall, Englewood Cliffs, New Jersey, 1990.

[47] R. Solera, F. Castillo, Materiales sintéticos en la impermeabilización. Seguimiento. CEDEX (Centro de Estudios y Experimentación de Obras Públicas), Alicante, 2001.

[48] I. Vaquero, Manual de Diseño y Construcción de Vertederos de Residuos Sólidos Urbanos. U.D.Proyectos, E.T.S.I.Minas - UPM, Madrid, vol. 360, 2004.

[49] J. Yack, E.J. O'Neill, Protective liner uses and landfill application, Groundwater Pollution Primer, CE 4594: Soil and Groundwater Pollution, Civil Engineering Dept. Virginia Tech., 1996, http://www.cee.vt.edu/ewr/environmental/teach/gwprimer/landfill/liner.html.

[50] D. Kumar, B.J. Alappat, Analysis of leachate pollution index and formulation of sub-leachate pollution indices, Waste Manage. Res. 22 (2005) 230–239.