Structural Safety 60 (2016) 117–129

Contents lists available at ScienceDirect

Structural Safety

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

Soil stochastic parameter correlation impact in the piping erosion failure estimation of riverine flood defences

J.P. Aguilar-López [a,*], J.J. Warmink [a], R.M.J. Schielen [a,b], S.J.M.H. Hulscher [a]

[a] University of Twente, Enschede, The Netherlands
[b] Rijkswaterstaat, Arnhem, The Netherlands

ARTICLE INFO

Article history:
Received 6 March 2015
Received in revised form 12 January 2016
Accepted 16 January 2016
Available online 14 March 2016

Keywords:
Piping erosion
Correlation
Sellmeijer
Failure probability
Copula
Flood defence

ABSTRACT

Piping erosion has been proved to be one of the failure mechanisms that contributes the most to the total probability of failure on the Dutch flood defence systems. The present study aimed to find the impact of correlation and tail dependence between soil parameters present in the Sellmeijer revised limit state equation for piping safety assessment, particularly between the grain size and hydraulic conductivity parameters. A copula based random sampling method was used as a tool to include this effect in the probabilistic estimation of this type of failure. The method was framed in a real case study for a flood defence along the Lek river, in The Netherlands. The results showed that inclusion of correlation between the two parameters reduces the variance of the limit state marginal distribution by almost 10% when compared to the uncorrelated case. This effect changes the tail values sampling frequency and therefore reduces the probability of failure by a factor of 1.7. The omission of correlation between the two parameters for safety assessment based on the Sellmeijer limit state function may result in over dimensioned structures.

1. Introduction

In The Netherlands, large flood risk assessment projects such as the VNK2 [1] have devoted great attention to develop and improve more robust probabilistic estimation methods for the safety assessment of their levee systems. One of the main results from this study was the prioritization of the different failure mechanisms that contribute the most to the total failure probability (Pf) of the levee systems. Reiteratively, piping erosion (PE) was found to be a major threat in most of the components of the system. This type of failure consists in a progressive erosion channel under the flood defence foundation which will eventually start a breaching process due to the loss of stability of the structure. This type of failure can be simulated by the numerical model developed by Sellmeijer [2]. For safety assessment, a revised limit state equation (LSE) [3] was derived based on this same model. This equation describes the safety state of the system given the most sensitive variables involved in the process for the occurrence of this particular failure mechanism. Limit state equations are implemented in probabilistic safety assessments as they can be used to expresses the loads experienced by the flood managing structure as a function of the water level probabilistic distribution. The resistance of the structure against these loads can also be represented as a probabilistic marginal distribution.

It is common in practice to assume that the random variables used for the limit state evaluation are represented by univariate probability density functions. Hence, they are commonly assumed as uncorrelated when no evidence is available. The omission of possible statistical dependence or correlation between different state variables is one major source of error in the failure estimation of reliability of a system when such variables are highly sensitive for the model probabilistic outcome. Correlation analysis is not only concerned about the degree of dependence but also the temporal and spatial distribution of the correlated random variables [1]. Extensive research has been done about the effect of spatial correlation of load and resistance of flood defences in The Netherlands [4–6]. Yet, the correlations were analyzed considering how a variable depends on itself (autocorrelation) along space and time and not within each other. The importance of variable correlation for flood defence structures was demonstrated in the study by Diermanse and Geerse [7] where the influence of bivariate

---

Abbreviations: PE, piping erosion; Pf, failure probability; LSE, limit state equation.

* Corresponding author at: Drienerlolaan 5, 7522 NB Enschede, The Netherlands.
E-mail addresses: j.p.aguilarlopez@utwente.nl (J.P. Aguilar-López), J.J.Warmink@utwente.nl (J.J. Warmink), R.M.J.Schielen@utwente.nl (R.M.J. Schielen), S.J.M.H.Hulscher@utwente.nl (S.J.M.H. Hulscher).

http://dx.doi.org/10.1016/j.strusafe.2016.01.004
0167-4730/

Sellmeijer revised LSE nomenclature

Zp	residual resistance (limit state) [m]
η	sand drag force factor (0.25) [–]
γ'_{sand}	unitary weight of submerged sand particles [kN/m^3]
γ_{w}	unitary weight of water [kN/m^3]
θ	bedding angle of sand grains [deg]
d_{70}	70 percent quintile value grain size distribution of sand layer [m]
$d_{70\mathrm{m}}$	calibration reference value (2.08×10^{-4} m) [m]
v	kinematic viscosity of water at 20 °C [m^2/s]
K	hydraulic conductivity of sand [m/s]
g	gravitational acceleration (9.81 m/s^2) [m/s^2]
D	average thickness of sand layer [m]
m_{p}	modelling uncertainty factor [–]
H_c	critical hydraulic head difference [m]

F_{R}	resistance factor [–]
F_{S}	scale factor [–]
F_{G}	geometric factor [–]
H_c	critical PE resistance head [m]
L	seepage length from entrance point to sand boil water exit [m]
H	water level in the foreside of the flood defence [m]
h_{b}	water level at hinterside outflow point [m]
d	impermeable layer thickness at the sand boil exit point [m]
Note	The product of the hydraulic conductivity of soil and kinematic viscosity divided by the gravitational acceleration is equal to the intrinsic permeability k [m^2] (noted as lower case k).

correlation modelling between two hydro climatological variables required for dike safety assessment was studied. One case study was done by modelling the inflows from the IJssel River and the water levels in the IJssel Lake, and another one for modelling the wind speeds and water levels in the North Sea coast correlated as well. Both case studies showed the influence that correlation modelling can have in the safety assessment of flood defences. Yet, the correlation impact was only studied in the variables involved for estimating the marginal distributions of the loads applied to the flood defences.

With this study it is intended to quantify the influence of correlation in failure estimation between two parameters present in the erosion model for piping assessment, in particular for a "single" cross section in a riverine flood defence when assessed by the revised Sellmeijer LSE [3]. This equation includes, the representative aquifer grain size parameters ($d70$) and the hydraulic conductivity parameter (K) which can be correlated for different models as presented by [8]. For the design and safety assessment of flood defences in The Netherlands, the dependence of these two parameters is considered by the empirical equation present in [9]. The drawbacks of this equation are that is only valid for sands with $d10 < 0.06$ mm and it also depends on a qualitative factor associated to the packing density of the particles in situ. Hence, the implementation of such equation in a fully probabilistic assessment (correlation inclusion) becomes unreliable. Note that the correlation addressed with this kind of equations (grain size versus hydraulic conductivity) represent the chance that the two variables are dependent disregarding their location (spatial correlation) in time and space (non-stationary process).

Despite including the dependence of these two parameters, the correlation degree between the two of them is not constant for all quantiles either. Base on the sample distribution, a higher correlation is expected for sands with larger percentages of smaller grains. Such variability of the correlation is known as tail dependence. This is also not included in the actual probabilistic assessment methods for flood defence reliability of PE and can have an important effect in the structure reliability.

During the PE process, only the most upper part of the aquifer is eroded which means that the $d70$ statistical distribution should be representative of mainly that zone. It is common to find finer grain distributions in the upper layer of the aquifers which will imply a lower correlation degree between the $d70$ and the K parameters. When the grain distribution of the most upper layer of the aquifer is significantly different and finer with respect to the one associated to the whole aquifer average distribution, the measured representative conductivity values for the whole aquifer can be assumed as uncorrelated. However, in the actual practice a detailed sampling procedure of only the upper layer of grain size and permeability is not practical for such longitudinal structures. Hence, the $d70$ and K statistical descriptors are estimated by indirect methods.

The fact that the upper layer may have a distinct granulometric distribution with respect to the lower layers, does not imply that correlation and/or tail dependence between $d70$ and K are negligible. It will only mean that the degree of dependence between the two parameters is lower than expected. Yet, this degree of correlation and tail dependence might change the probabilistic outcome if found significant enough. It is also important to state that not all variables involved in this process necessarily should be considered as correlated, despite the fact that significant correlation can be estimated from their dataset. Sufficient physical evidence of the origin of the correlation should be proven before deciding to include its effect in a structural reliability assessment. In other words correlation does not necessarily implies causation.

For the data of an existent river flood defence located in The Netherlands along the Lek river, the correlation and its physical origin were studied.

In order to structure the research, three main questions were addressed:

1. Is there considerable correlation between the representative grain size ($d70$) and the hydraulic conductivity (K)?
2. How to select and validate a correlation bivariate model (copula family) for the failure estimation due to piping?
3. How important is the impact of correlation between $d70$ and K in the failure probability estimation due PE when estimated by Sellmeijer revised limit state equation?

The outline of the paper consist in the physical process of the PE failure mechanism and its limit state function which are explained in detail in Section 2, plus the implementation of the copula functions for generating the correlated random samples. In Section 3 the case study and the input data used for the failure estimation are described. Section 4 describes the results obtained from estimating correlation from the field collected data. In Section 5 the selection and validation of a model that describes best the soil behaviour is presented. In Section 6, the results of the correlation effect on the limit state function marginal distribution and failure probabilities are presented. In Section 7, the results of each research question are discussed and finally the main conclusions of the study are presented in Section 8.