Safety assessment of the existing earth levees: estimation of composition, state and stability

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Abstract: In present paper we focus on the procedure for assessment of existing levee composition, state and stability, based on the results of field and laboratory investigation, and following the positive international recommendations in this field. For this purpose, we classify main types of levees in Serbia, including the main categories of levee failure. As a results of research, we propose statistically reliable correlations among the grain size composition, results of penetration tests and specific electrical resistivity, in order to estimate the composition and state of the existing levee. Regarding the stability, we develop separate stability diagrams for assessment of construction and filtration stability, for levees with different composition and geometry, assuming common range of values of input geomechanical parameters.

INTRODUCTION

According to the International Levee Handbook (ILH) [1], earth levees (flood embankments or dikes) represent vital elements of a modern flood risk management, commonly raised along the major rivers passing through inhabited areas as an integral component of a flood protection system. Despite the capital importance of these constructions for flood management authorities, it should be emphasized that according to international and domestic experience from engineering practice, the greatest part of these so-called "major" levees (along large rivers with the primary aim of protection from high waters) is over several decades old, without the reliable historical records on the results of investigation works (before the construction), properties of earth material, design, construction and/or historical performance. Considering this, maintenance of such levees is tightly connected to specific investigation works which should enable reliable assessment of their construction (geometry and spatial distribution of different earth materials) and current state. Such assessment forms then a solid basis, i.e., adequate support for an effective decision-making regarding the need for levee reconstruction, which includes: modelling of levee behavior in different extreme conditions, identification and spatial differentiation of weak zones and corresponding optimal design of levee reconstruction.

Common methods for investigation and maintenance of existing levees are usually (1) invasive, (2) time consuming, (3) with high level of uncertainty, and (4) could lead to unreliable conclusions which are not on the safe side. Invasivity of common methods lies in the massive use of drilling, which represents obligatory but punctual method for determining the composition of the earth levee: punctuality of recorded data further assumes interpretation of the levee composition between the conducted boreholes, which increases the level of uncertainty. Such methods are also time consuming since drilling with laboratory analyzes assumes a solid period for preparing adequate picture of earth levee composition. According to our experience, for 30km long levee it takes approximately 6 months to obtain relevant results and propose adequate assessment of levee composition and state. On the other hand, levee monitoring is conducted by field reconnaissance and visual inspection, while additional investigation works are done only in case when levee reconstruction is planned. Currently, in general there are no clear national methods for management of levee maintenance and traditional visual monitoring of levee state predominates, which do not always provide reliable results. For instance, a survey of levee failures during the 2002 flood in Germany [2] and an analysis for the last 10 years of levee failures in England [3] showed that the levees broke at sections that were considered to be safe according to conventional levee assessments [4].

There is a strong branch of researchers who have been developing different systems and methods for intelligent monitoring of levees to enhance the possibility of early warning. This commonly includes two directions: (1) analysis of airborne / satellite images via remote sensing techniques [5-6], (2) installation of sensors for measurement of earth and pore pressure, meteo stations, piezometers, inclinometers, geodetic benches at the ground surface and similar [7-9], which enable the recording of large number of data that could be used for further analyzes. Application of remote sensing to detect possible anomalies in the existing levee construction could be useful, but are frequently aggravated by thick vegetation, possible occurrence of wet zones, bad weather conditions etc. Majority of these obstacles could be overcome using modern satellite images from different electromagnetic specter. Nevertheless, such analyzes could provide only the first preliminary information on the possible locations of "weak" zones along the existing levees. On the other hand, from pure engineering point of view, development and installation of smart equipment for continuous (permanent) monitoring of levees is questionable, since flood management authorities and community in general are interested in knowing the composition and state of the levee, with further stability assessment to establish possible weak places which could be improved, rather than to install a system which will tell them when the critical period is and what the critical places are during the critical period. This critical period for each levee is obvious – during high waters (floods), whose duration is not long and during which the nearby community is alarmed, and additional measures are applied at certain points if needed. Therefore, we consider that further development of smart systems for levee monitoring is no justified. Instead, we are proposing concept and methodology for reliable assessment of levee composition, current state and stability by tracking the following principles: (1) maximum reliance on the results of previous investigation works in similar geological environments (maximum use of previous results); (2) maximum reduction of invasive investigation works (minimum invasivity); (3) maximum use of non-invasive investigation works, including geophysics, CPT and DPSH tests (maximum non-invasivity); (4) maximum use of construction and filtration stability analyzes by setting up adequate experimental design (maximum stability analyzes); (5) maximum use of statistically significant correlations (statistical significance); (6) maximum use of Eurocode (EC-7) [10] and International Levee Handbook (ILH) guidance (positive regulation obedience). As an outcome, we suggest: (1) statistically significant correlations between the specific electric resistivity of different earth materials and the measures of their compressibility state (according to the results of drilling, laboratory and penetration tests); (2) diagrams of levee constructive stability; (3) diagrams of levee filtration stability. Considering the similar geological environments from which the earth material for levee construction is borrowed (alluvial plain in the downstream parts of large rivers) and the similar disposition of levees and the corresponding river, one may consider suggested correlations as almost universal, which could be, with sufficient confidence, used for almost all types of levee construction in Serbia. For other countries, our approach could be treated as methodological, i.e., by following the same steps, one could arrive at the significant correlations and stability diagrams for other construction and states of levees in different geological conditions. One should note that derivation of statistically significant correlations among different geomechanical parameters and construction of stability diagrams does have a previous history at Jaroslav Černi Water Institute (JCWI). As a pioneer work, Kostić et al. [11] developed a series of slope stability diagrams for homogeneous coherent slopes, based on the nonlinear dependence of slope stability on physical and mechanical soil properties and groundwater impact. Based on these investigation works, two new technical solutions were developed at JCWI and applied in engineering practice [12]. Additionally, JCWI has a long history of levee monitoring within the Project of permanent monitoring of the state of protection system from the influence of HPP "Iron Gate 1" in the coastal region and working efficiency of the system through Program VII: Program of investigation works for determining of the effect of on levees' stability [13]. Monitoring of levees' stability within this Program have been conducted since 1978. In the period 1978-2010 this monitoring activity included only the visual observation of levees' state and recommendations for levee reconstruction at the spotted weak points. Since 2010 his Program includes the conduction of investigation works, in order to determine composition, state and stability of existing levees which are under influence of the HPP "Iron Gate 1".

TYPES OF LEVEE CONSTRUCTION IN SERBIA

There are many variations of levee construction, depending on the levee type (main, summer, peripheral etc), position of the levee regarding urban areas and the availability of the construction material. In the previous period, in order to monitor the condition of the levee which are under the impact of HPP "Iron Gate 1", JCWI carried out investigation works along the certain sections of existing levees where deformation were observed, both on the body of the embankment itself and on the near-embankment area. According to the results of investigation works conducted by JCWI, there are several main types of levee construction in Serbia (Figures 1 and 2).

Although there are many different constructions of levees, one could single out three main types, which occur most frequently, and which will be analyzed in present paper: levees built of coherent material (1), incoherent material (2) and mixed coherent and incoherent material (3).

The first type represents coherent levee composed of clay and silt at the water side of the levee, whereas the land side of the levee is built of sand and silt, i.e., dredged material as ballast. Representative of this type is the levee along the Danube River at the Gradištansko island, where the presence of impermeable clay-silty materials can be clearly observed at the water side of the levee, while the water-permeable silty-sandy materials compose the land side of the levee (Figure 3).

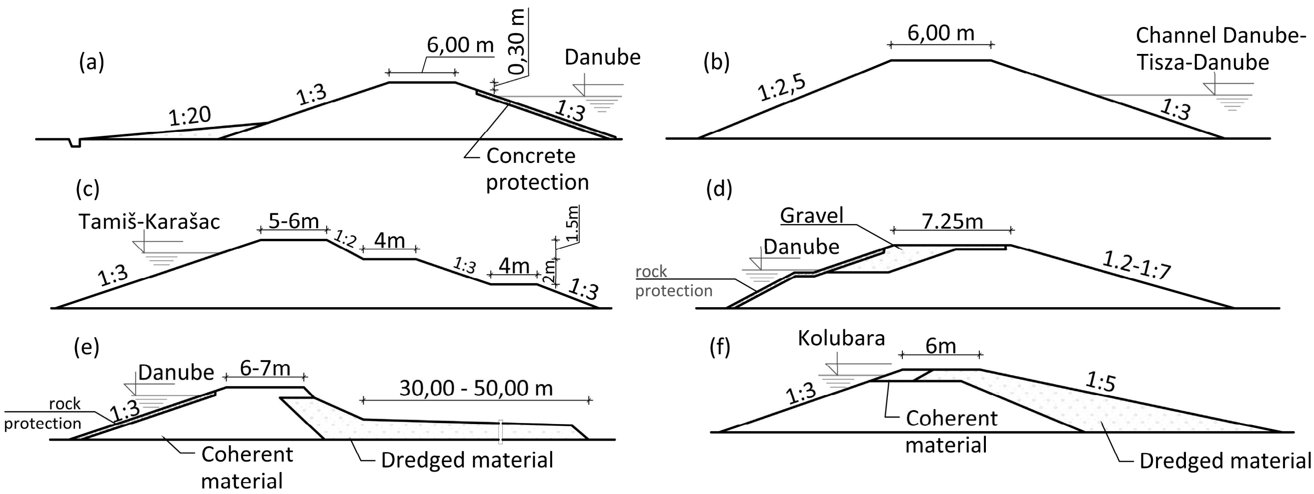

Figure 1. *Main types of levees in Serbia, according to the results of research performed by JCWI: (a) levee Pančevo-Dubovac, (b) levee along the left coast of the Nadela channel; (c) levee next to Tamis and Karašac in Pančevački Rit; (d) characteristic Danube levee; (e) characteristic Danube levee at Gradištansko island; (f) levee along the left coast of the Kolubara river*

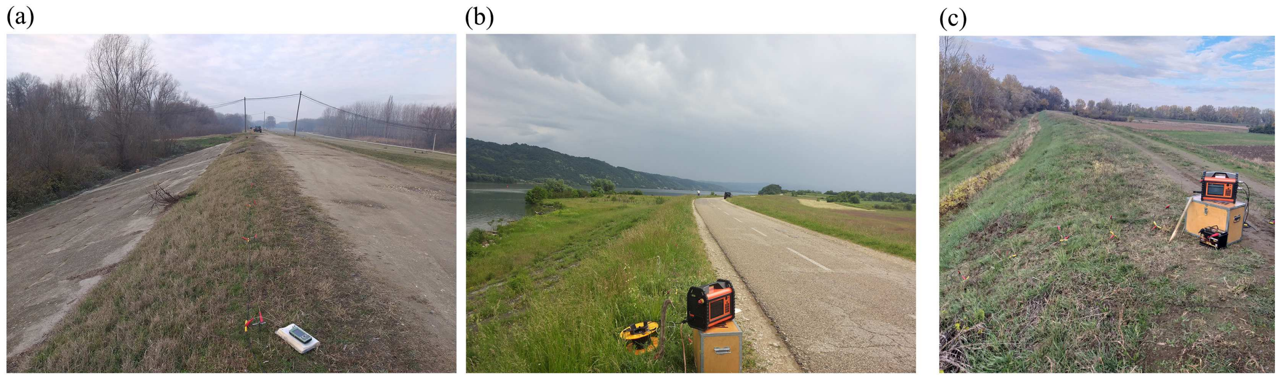

Figure 2. *Illustration of different levee types in Serbia: (a) levee with concrete protection on the water side along the Danube (Pančevo-Dubovac); (b) levee crown used as local road, Gradištansko island; (c) typical earth levee along the left coast of the Kolubara river (photo R. Vasić and B. Stanković)*

The second type represents incoherent levee predominantly composed of sand with variable fraction of gravel. Representative example of this type is the levee along the right coast of the Kolubara River, where almost the entire levee is built of sandy sediments, with silty materials that compose only the superficial parts of the water side of the levee (Figure 4). Similar type of levee is detected on along the channel ''Danube-Tisza-Danube'' (DTD) where the whole levee is built of incoherent material from the excavation of the DTD channel (Figure 5).

The third type, and the most common one, represents the levee composed of mixed coherent and incoherent material (Figure 6). The body of the levee consists of coherent clayey and silty sediments. In the superficial parts of the crown of the levee, dry and well-compacted sandy silty are present, but sometimes gravel may also occur near the surface. Superficial part of the land side of the levee is composed of dredged sandy materials, while the water side of the levee is protected by concrete or stone lining. Representative example of this type is the levee along the left coast of the Danube River at Pančevački rit. The body of the levee consists of coherent clayey and silty sediments while on the in the defended part, while the land side is composed of water-permeable silty-sandy materials, including ballast built of dredged material.

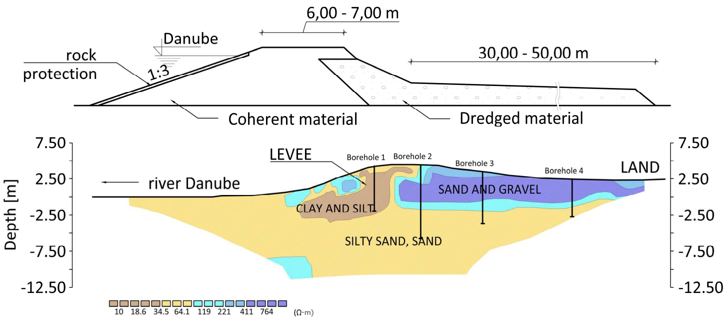

Figure 3. *Representative of Type 1 levee - Gradištansko island – right bank of the Danube River: (a) schematic transverse cross-section, (b) 2D inverse resistivity cross-section*

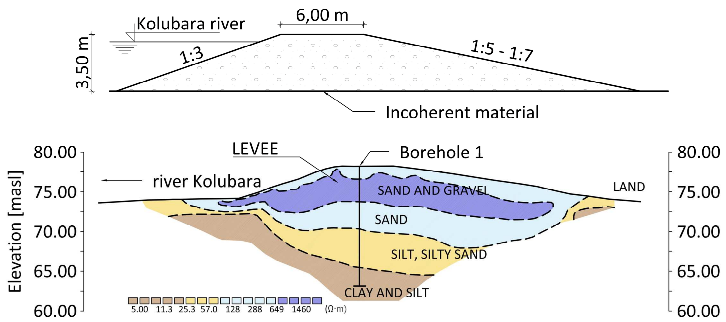

Figure 4. *Representative of Type 2 levee - right coast of the Kolubara river: schematic transverse cross-section and 2D inverse resistivity cross-section*

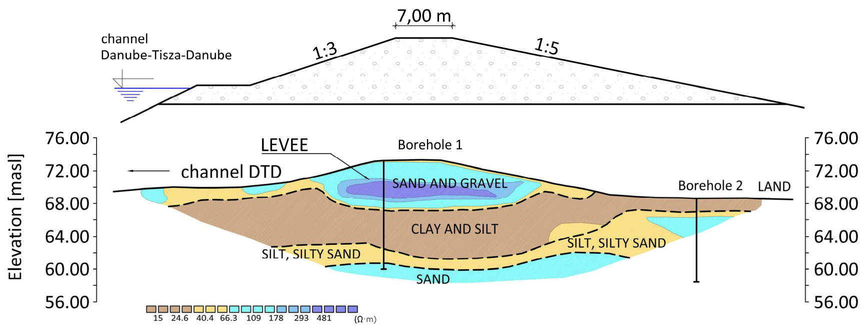

Figure 5. *Representative of Type 2 levee - left bank of the channel DTD: schematic transverse cross-section and 2D inverse resistivity cross-section*

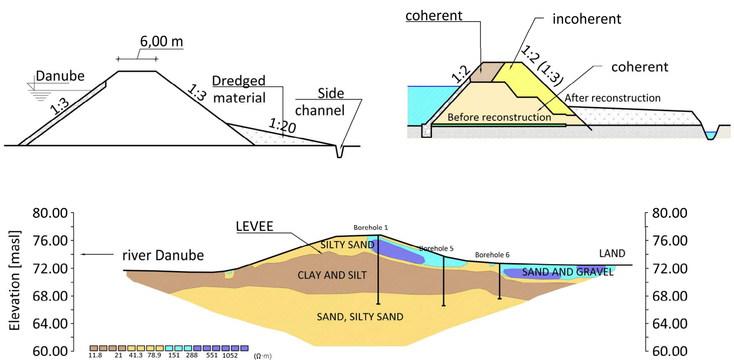

Figure 6. *Representative of Type 3 levee - left bank of the Danube River (Pančevački rit): schematic transverse cross-section and 2D inverse resistivity cross-section*

RECOMMENDATIONS FROM REGULATORY DOCUMENTATION

Let us first briefly introduce the recommendations regarding the analysis of existing and design of new levees from the old domestic (national) rulebooks [14], from Eurocode [10,15] and International Levee Handbook [1].

Old national rulebooks foresee using of technical requirements for design of dams and hydrotechnical embankments (JUS U.C5.020, [14]). For design of the levees rulebook define several basic calculations, such as: calculation of a filtration field of the embankment (5.2.1), calculation of a filtration – erosion stability of the embankment (5.2.2), calculation of filter zones of the embankment (5.2.3), calculation of the protective lining of the upstream – water slope of the embankment (5.2.4), slope stability analysis of the embankment (5.2.5), deformation analysis of the embankment (5.2.6), calculation of the width of the crest of the embankment (5.2.7) and calculation of free height of the embankment (5.2.8). Next to this basic calculation there is also a structural design (6) and embankment observation (7). All this calculation should be verified during the design stage. One should note that these old rulebooks did not consider any investigation works or re-design of the existing levees.

EC7 foresees that the levee design should be executed with previously determined geotechnical design requirements, by placing the designed structure into the appropriate "geotechnical category" (Table 1).

Table 1. *Geotechnical categories according to EC7*

Geotechnical category	Scope of category
Geotechnical category 1	Include only small and relatively simple structures for which it is possible to ensure that the fundamental requirements will be satisfied on the basis of experience and qualitative geotechnical investigations and with negligible risk.
Geotechnical category 2	Include conventional types of structures and foundation with no exceptional risk or difficult soil or loading conditions such as: spread foundations, raft foundations, pile foundations, walls and other structures or supporting soil or water, excavations, bridge piers and abutments, **embankments (levees) and earthworks**, ground anchors and other tie-back systems, tunnels in hard, non-fractured rock and not subjected to special water tightness or other requirements.
Geotechnical category 3	Include structures or part of structures, which fall outside the limits of Geotechnical categories 1 and 2, such as: very large or unusual structures, structures involving abnormal risk, or unusual or exceptionally difficult ground or loading conditions, structures in highly seismic areas, structures in areas of probable site instability or persistent ground movements that require separate investigation or special measures.

During the design phase, the following design situations must be considered:

- Long-term design situations (EC7/1, 2.2) (normal operating conditions),
- Short-term design situations (EC7/1, 2.2) (transitory conditions, for example during the construction or repair),
- Seismic design situations (EC8) (structure is exposed to earthquakes), and
- Accidental design situations (EC1, 1.7) (such as an appearance of earthquakes in areas of high seismicity, or the occurrence of flooding with a higher return period than calculated).

Calculations in EC-7 are done by using the design values of parameters (actions, geotechnical parameters, geometrical data etc.), Table 2, which are based on characteristic and representative values. Characteristic values are values that with a certain probability will not be exceeded during the operational life of the structure, determined as the middle, upper (95%) or lower value (5%) of a normal (Gaussian) distribution depending on the type of effect. The representative value is the characteristic value of the action weighted by the coefficients for combining ψ_i, which consider the fact that the probability of the simultaneous action of several variable (incidental) actions is reduced in the full amount.

In the design phase ultimate limit state (ULS) and serviceability limit state (SLS) following limit states must not be exceeded. There are five ultimate limit state (ULS) (EC7/1, 2.4.7.1):

- (EQU), loss of equilibrium of the structure or the ground, considered as a rigid body, in which the strengths of structural materials and the ground are insignificant in providing resistance,
- (STR), internal failure or excessive deformation of the structure or structural elements, including e.g. footings, piles or basement walls, in which the strength of structural materials is significant in providing resistance,
-

- (GEO), failure or excessive deformation of the ground, in which the strength of soil or rock is significant in providing resistance,
- (UPL), loss of equilibrium of the structure or the ground due to uplift by water pressure (buoyancy) or other vertical actions,
- (HYD), hydraulic heave, internal erosion and piping in the ground caused by hydraulic gradients.

Table 2. *Design values of actions and geotechnical parameters*

Design values of actions	Design values of geotechnical parameters
$F_d = \gamma_F \cdot F_{rep}$, $F_{rep} = \psi \cdot F_k$, F_d - design value of the action, F_{rep} - representative value of the action, F_k - characteristic value of the action, γ_F - partial factor for persistent and transient situations (**design approach depended**), ψ - coefficient for combining	$X_d = \frac{X_k}{\gamma_M}$, X_d - design value of geotechnical parameter, X_k - characteristic value of the geotechnical parameter γ_m- partial factor for persistent and transient situations **(design approach depended)**, negligible risk.

For the levee design all five ultimate states are important, while the EQU state is less important (the possibility of occurrence is very unlikely). For STR and GEO limit states, following should be verified (EC7/1, 2.4.7.3.1): $E_d \leq R_d \rightarrow E_d / R_d \leq 1$, where E_d is design effect of actions, R_d is design resistance. For STR and GEO, EC7 define three Design approaches ("DA"): (1) A1+M1+R1, A2+M2+R1, (2) A1+M1+R2, (3) (A1 or A2) +M2+R3. Every country chooses their own DA through National Annex, and the Republic of Serbia choose DA-3 for designing of slope stability [10], and therefore for the design of levee structures. These approaches refer to the groups of materials (M), actions (A), and resistance (R), by applying partial factors to corresponding groups factors, in accordance with Table 3.

Table 3. *Partial factors for actions (A), reactions (R) and soil parameters (M)*

Action		Symbol	Set		
			A1		**A2**
Permanent	Unfavourable	γ_G	1.35		1.00
	Favourable		1.00		1.00
Variable	Unfavourable	γ_Q	1.50		1.30
	Favourable		0.00		0.00
Resistance		Symbol	Set		
			R1	R2	**R3**
1		$\gamma_{R;v}$	1.00	1.40	**1.00**
2		$\gamma_{R;v}$	1.00	1.10	**1.00**
Soil parameter		**Symbol**	**Set**		
			M1		**M2**
Angle of internal friction[a]		$\gamma_{\phi`}$	1.00		**1.25**
Effective cohesion		$\gamma_{c`}$	1.00		**1.25**
Undrained shear strength		γ_{cu}	1.00		**1.40**
Unconfined strength		γ_{qu}	1.00		**1.40**
Unit weight		γ_{γ}	1.00		**1.00**

[a]this factor is applied to tanϕ'

For UPL and HYD – both limit states are considered as a hydraulic failure (EC7/1, 10.1), and the following should be checked:

- Failure by uplift (UPL) (EC7/1, 2.4.7.5 & 10.3)
- When considering a limit state of failure due to heave by seepage of water in the ground it shall be verified, for every relevant soil column, that the design value of the destabilizing total pore water pressure at the bottom of the column, or the design value of the seepage force in the column is less than or equal to the stabilizing total vertical stress at the bottom of the column, or the submerged weight of the same column. For UPL, limit state (EC7/1, 10.2) is checked against failure by uplift using inequality (EC7/1, (2.8)) and (EC7/1, 2.4.7.4.) $V_{dst,d} \leq G_{stb;d} + R_d$, where $V_{dst,d}$ is sum of destabilizing permanent and variable action, $G_{stb;d}$ is stabilizing permanent actions, R_d is additional resistance to uplifting and $V_{dst,d} = G_{dst;d}$ (permanent destabilizing actions) + $Q_{dst;d}$ (variable destabilizing actions), Table 4.
- Failure by heave (HYD) (EC7/1, 2.4.7.5 & 10.3)
- EC7/1 takes into consideration the heave under the stabilizing wall. When considering levees, critical heave is heave through the body of the levee or through the levee and subsoil. The stability of soil against heave shall be checked by verifying one of the following equations: $u_{dst;d} \leq \sigma_{stb;d}$, $S_{dst;d} \leq G'_{stb;d}$ where $u_{dst;d}$ is design value of the destabilizing pore water pressure at the bottom of the soil column, $\sigma_{stb;d}$ is stabilizing total vertical stress at the bottom of the column, $S_{dst;d}$ is design value of the seepage force in the column, $G'_{stb;d}$ is the submerged weight of the same column, Table 4.
- Internal erosion (HYD) (EC7/1, 10.4)
- Internal erosion usually appears in zoned parts of levees when the filter sheets are not applied. EC7/1 generally propose checking of filter criteria and/ or applying artificial filter sheets and checking of critical hydraulic gradient, taking into consideration the following aspects: direction of flow, grain size distribution and shape of grains and stratification of the soil.
- Failure by piping (HYD) (EC7/1, 10.5)
- Piping is the phenomenon of the removal of particles from the foundation soil with an unfavorable grain size composition, under certain hydromechanical conditions. Such failure is prevented ither by the application of filters or by taking structural measures to control or to block the ground-water flow.

Table 4. *Partial factors on actions (UPL), soil parameters and resistances (UPL), and actions (HYD)*

Action	Symbol	Partial factor on actions (UPL) (γ_F)	Partial factors for soil parameters and resistances (UPL)	Partial factors on actions (HYD) (γ_F)
Permanent				
Unfavourable[a]	$\gamma_{G;dst}$ (factor on destabilising unfavourable permanent actions)	1.00	1.00	1.35
Favourable[b]	$\gamma_{G;stb}$ (factor on stabilising favourable permanent actions)	0.90	0.90	0.90
Unfavourable[a]	$\gamma_{Q;dst}$ (factor on destabilising unfavourable variable actions)	1.50	1.50	1.50

[a] Destabilising, [b] Stabilising

SLS (EC7/1, 2.4.8 & 12.6(1)P)

When checking serviceability limit state design of levee, it is necessary to check that the deformation of the levee does not lead to the occurrence of a serviceability limit state in either the levee or any adjacent structures, roads or services. Verification for serviceability limit states in the ground or in a structural section, element or connection, shall either require that Ed ≤ Cd → Ed / Cd ≤ 1, where E_d is design effect of actions and C_d is limiting design value of the effect of an action.

One should note that EC7 does not consider any investigation works or re-design of the existing levees.

ILH [1] defines several actual methods to analyze stability for various physical processes that could lead to levee deterioration or failure (Figures 7-9): water-levee interaction, structural performance, and functional performance and post failure analyses.

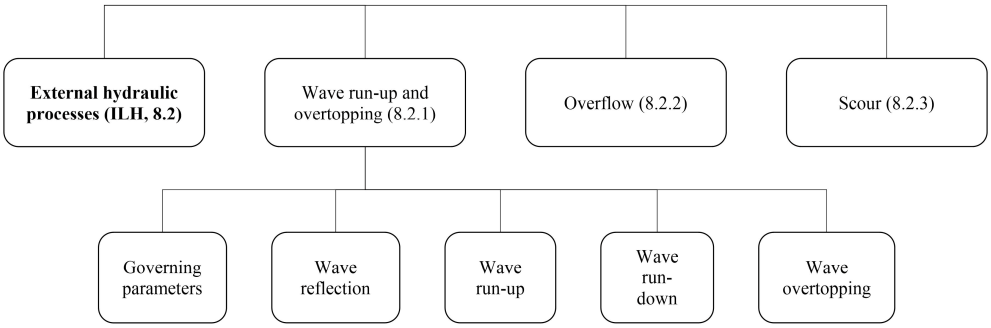

Figure 7. *Water – levee interactions*

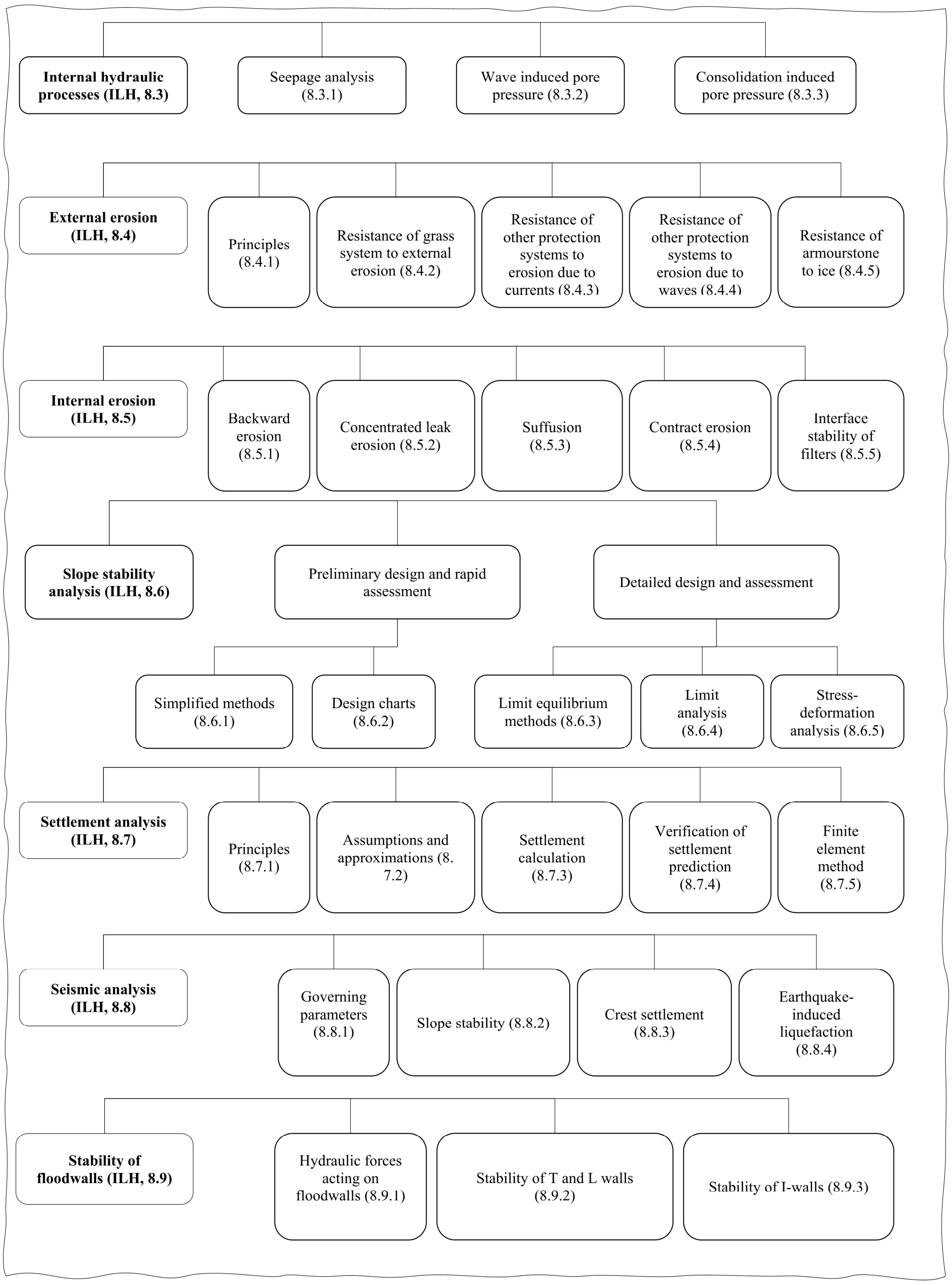

Figure 8. *Structural performance*

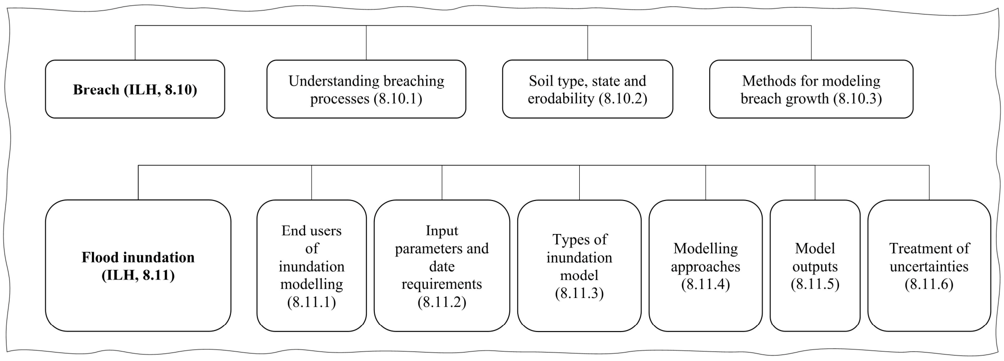

Figure 9. *Functional performance and post failure analyses*

Water-levee interactions and structural performance should be checked by the designers in accordance with the recommendations from ILH for a specific type of the levee. Stability calculation generally use the traditional global factor ("lumped factor") – preferably in the US or "characteristic" values if actions (loads) and resistance (strengths) – preferably in the EU countries (EC7). In the traditional global factor ("lumped factor") approach, the margin of the resistance to failure (in terms of forces or moments) to the destabilizing forces (or moments) is expressed as the "factor of safety". In this approach, the calculation uses characteristic, representative or moderately conservative values of geotechnical parameters. The partial factor approach now adopted in the Eurocodes in which independent 'partial' factors are applied to different actions (loads) and resistances (strengths) so that ultimate limit state (ULS) or serviceability limit state (SLS) calculations can be performed. Partial factors are applied to either the actions (applied loads, forces, etc.) or the resistances (material strengths, etc.) or both.

TYPES OF LEVEE FAILURE IN ENGINEERING PRACTICE

According to data given in ILH [1], statistical analysis for levee failure in Germany on the flood event of August 2002 in Saxony rivers for 84 records of levee failure (100 levee breaches were reported), resulted in the following classification of the main causes of levee breaches:

- 70.2% (59 cases) due to external erosion (mainly due to overtopping)
- 16.7% (14 cases) due to stability failure (slope failure)
- 9.5% (8 cases) due to subsoil failure (hydraulic uplift etc.)
- 3.6% (3 cases) due to internal erosion (e.g. piping).

Additionally, according to levee failure statistics on the flood events developed in France within a national research project called ERINOH (2006-2012), out of the 120 records, the main failure causes of breaches are classified as follow:

- 16% (19 cases) due to internal erosion (the location of pipes or burrows are explicitly mentioned in 11 cases)
- 41% (50 cases) due to overtopping
- for 43% (51 cases) causes of breaches were not identified.

In Serbia, according to the results of investigation works done by JCWI, the following types of levee deformation were recorded:

- filtration instability (groundwater flow below the levee and overflowing on the land side, with or without internal erosion and removal of the small sand particles), Figure 10 (a) and (b):
- instabilities of levee slopes, Figure 10 (c);
- levee breaching, as it was recorded during the floods in 2014 (levee along the channel Čikovac on the left coast of the Kolubara river).

Present analysis includes the first two most frequent types of levee deformation in Serbia. Levee breaching is considered as the most severe deformation, as an ultimate consequence of the mutual effect of water force, erosion, slope instability and piping, and it cannot be easily simulated in numerical calculations.

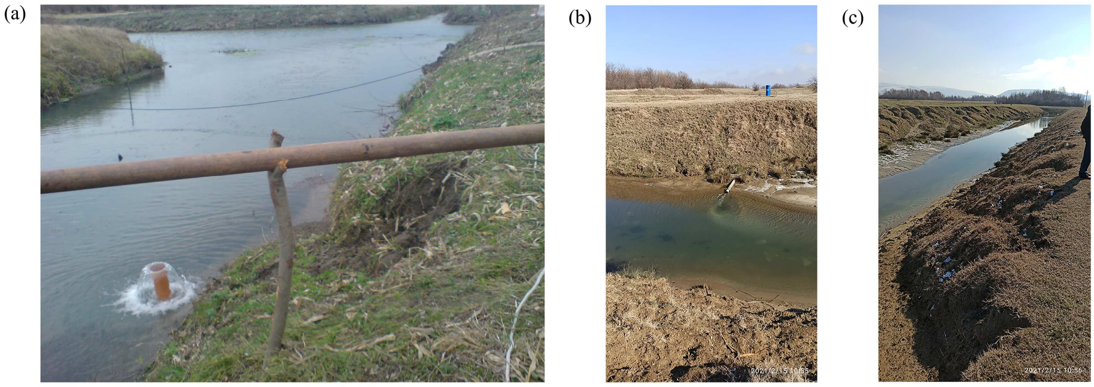

Figure 10. *Water overflow from piezometer pipe in the bottom of lateral channel (land side of the levee) (a); water boiling at the bottom of lateral channel (b); Instability of the land side slope (c) (photo B. Stanković)*

EMPIRICAL RELATIONS FOR ASSESSMENT OF LEVEE COMPOSITION AND STATE

Since 2014 JCWI introduced non-destructive geophysical research using the geoelectrical tomography method as an auxiliary geotechnical investigation tool for subsurface soil investigation, as a part of Project of permanent monitoring of the state of protection system from influence of HPP "Iron Gate 1" in the coastal region and working efficiency of the system through Program VII: Program of investigation works for determining of the effect of on levees' stability.

The goal of applied geophysical measurements was to make contribution to estimation of the composition of the existing levees predominantly from the aspect of its water holding capacity or water permeability. The methodology applied involved placing profiles along the levee and perpendicular to the levee in the zones of interest. Since sections up to 1 km were examined, in order to achieve continuity of measurement and the corresponding horizontal and vertical resolution of the measured data a "roll along" technique was applied through application of modern multi-electrode Terrameter Lund System (Figure 11).

Field geotechnical investigation works were conducted together with terrain geophysical measurements, including borehole drilling, core sampling and laboratory testing, CPT and SPT tests (Figure 12). In present paper, we analyze all the collected data in order to establish the reliable correlations among different results, with the final goal of assessing the levee composition and compressibility state solely based on the result of geophysical – geoelectric measurements.

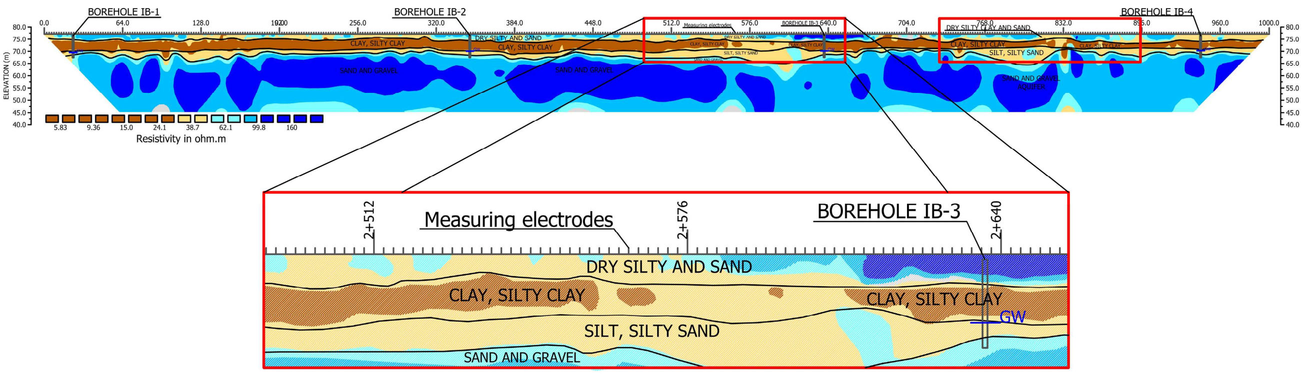

Figure 11. *Longitudinal profile on the levee on the river Tamiš, the left tributary of the Danube - inverse model resistivity section with a geological interpretation of the results, with a clearly defined break in the continuity of the clay core of the levee*

In order to establish statistically significant and physically possible correlations among different measured parameters, we examined the total number of 199 data (Table 5). Possible correlations between data were analyzed using multiple linear regression technique, with ANOVA testing and calculation of basic statistical parameters (determination coefficient, mean squared error, etc.).

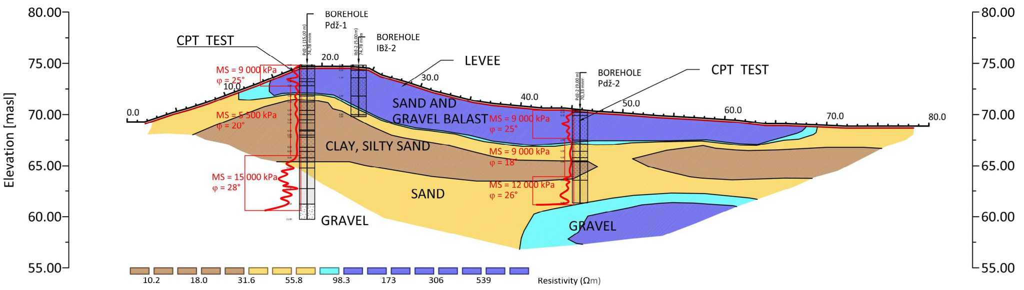

Figure 12. *2D inverse resistivity cross-section of the levee along the left coast of the Danube River with geological interpretation (based on the results of drilling and laboratory testing) and CPT test*

Table 5. *Analyzed parameters and range of their values*

Parameter	Min	Max	Average
% of clay	0	45	12.6
% of silt	0	87.7	46.7
% of sand	1	97	36.3
% of gravel	0	74.7	12.7
q_c measured from CPT (MPa)	0.6	25.1	4.1
Ms calculated from CPT (kPa)	1000	52350	9214
Number of blows per 30cm from SPT	4	82	19
Specific electric resistivity ρ (Ωm)	5	1147	122.1

Results of conducted analyzes indicate that physically possible and statistically significant correlations could be established among specific electrical resistivity, grain size and compressibility state of the existing levee. Regarding the relations between composition and soil resistivity, physically possible and statistically significant correlations are obtained between the soil resistivity and (1) the coherent/incoherent fraction percentage (Figure 13a) and (2) sand/gravel fraction percentage in predominantly incoherent earth levees (Figure 13b). One should note that no statistically significant correlations could be established between soil resistivity and silt/clay fraction percentage in predominantly coherent materials.

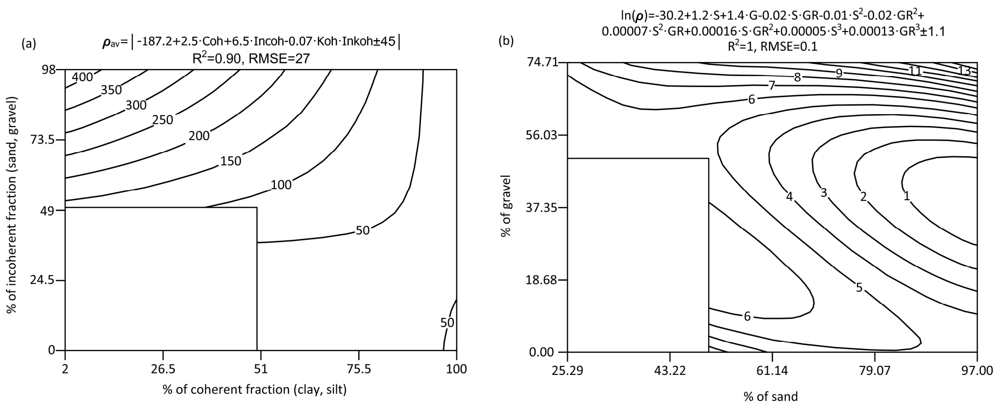

Figure 13. *Correlations between soil resistivity and (a) coherent/incoherent fraction percentage, (b) sand/gravel fraction percentage in predominantly incoherent earth levees*

As for the relations between soil resistivity and compressibility state, physically possible and statistically significant correlation could be obtained between average soil resistivity ρav and (1) soil compressibility modulus (Ms) according to the results of CPT tests for predominantly both incoherent materials and coherent materials (Eq.1), (2) average cone resistance per layer qcav from CPT test for predominantly coherent materials (Eq.2):

$\ln(Ms) = 8.4 + 0.01 \cdot \rho_{av} - 0.00003 \cdot \rho_{av}^3 + 0.00000003 \cdot \rho_{av}^3 \pm 0.85$, ...$R^2$=1, RMSE=0.25 (1)

$q_{cav} = 0.16 + 0.08 \cdot \rho_{av} - 0.00008 \cdot \rho_{av}^2 \pm 2.7$, ...$R^2$=0.98, RMSE=0.25 (2)

One should note that no statistically significant correlations could be established between cone penetration resistance (from CPT) and specific electric resistivity in predominantly incoherent materials, nor between SPT number of blows and specific electric resistivity in predominantly coherent materials.

LEVEE STABILITY DIAGRAMS

Structural stability

In order to derive structural stability diagrams we analyze the following three types of levees in Serbia (Figure 14 and Table 11):

- Type 1 - levees composed of cohesive materials (silt and clay)
- Type 2 - levees composed of cohesionless material (sand and gravel)
- Type 3 - levees composed of mixed cohesive and cohesionless material.

The following cases of stability are examined:

- case study 1: maximum water level on the water side, 1m below the crown. Stability of land side slope is examined;
- case study 2: rapid drawdown, from 1m below the crown to the levee foot for 12h (half a day). Groundwater level – filtration line was calculated using finite element analysis. Stability of water side slope is examined.

For all the examined cases, output parameter is the slope safety factor. Calculations were done using the Spencer method which satisfies all the force and moment equilibrium conditions. Material properties are defined under the assumption of Mohr-Coulomb failure criterion. For the input data shown in Table 6, the adequate experimental design was set up, using the Box-Behnken approach. For each chosen height (3,5,7m) 17 runs were examined (with 5 centers per block) for Type 1, while for Type 2 levee height was also included as variable parameter. For Type 3, for each chosen height (3,5,7m) 29 runs were examined (with 5 centers per block). Results of the analysis for the most critical cases (the lowest examined values of cohesion and friction angle, and for the highest levee) are shown as separate diagrams in Figure 15.

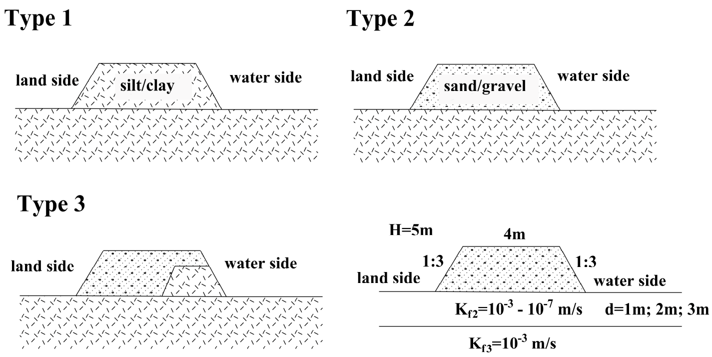

Figure 14. *Types of levees singled out for the analyzes*

As a result of performed analyzes, we obtained explicit mathematical expressions for levee slope safety factor as a nonlinear function of the examined input factors. Some illustrative examples of these equations are given below:

$Fs = 0.67 - 0.06 \cdot \beta + 0.09 \cdot c + 0.06 \cdot \varphi - 0.0015 \cdot \beta \cdot c - 0.0015 \cdot \beta \cdot \varphi + 0.00035 \cdot c \cdot \varphi + 0.0014 \cdot \beta^2 - 0.00025 \cdot c^2 + 0.00016 \cdot \varphi^2$, ….. for Type 1, case study 1, H=7m, R^2=0.99, RMSE=0.0023 (3)

$Fs = 2.19 - 0.08 \cdot \beta - 0.32 \cdot H + 0.066 \cdot \varphi + 0.006 \cdot \beta \cdot H - 0.0012 \cdot \beta \cdot \varphi - 0.004 \cdot H \cdot \varphi + 0.001 \cdot \beta^2 + 0.016 \cdot H^2 + 0.0004 \cdot \varphi^2$, ….. for Type 2, case study 2, R^2=0.99, RMSE=0.0035 (4)

$$Fs = 0.68 - 0.045870 \cdot \beta + 0.095 \cdot c_1 + 0.22 \cdot \varphi_1 - 0.11 \cdot \varphi_2 - 0.0024 \cdot \beta \cdot c_1 - 0.0054 \cdot \beta \cdot \varphi_1 + 0.0025 \cdot \beta \cdot \varphi_2 - 0.0033 \cdot c_1 \cdot \varphi_1 + 0.0034 \cdot c_1 \cdot \varphi_2 + 0.005 \cdot \varphi_1 \cdot \varphi_2 + 0.0012 \cdot \beta^2 - 0.0024 \cdot c_1^2 - 0.0052 \cdot \varphi_1^2 - 0.00087 \cdot \varphi_2^2, \; \ldots \text{ for Type 3, case study 1, } R^2=0.98, \text{ RMSE}=0.019 \quad (5)$$

Table 6. *Range of values for input data for different analyzed types of levee. Fixed parameter values are: for underlaying layer: γ=19 kN/m³, c=25 kPa, φ=20°; for levee: γ=19 kN/m³, crown width: 5m*

Types	Type 1		Type 2		Type 3	
Input data	Min	Max	Min	Max	Min	Max
Levee height, H (m)	3	7	3	7	3	7
Inclination of levee slopes, symmetrical, β (°)	18	27	18	27	18	27
Cohesion, c1 (kPa)	5	15	/		5	15
Cohesion, c2 (kPa)	/	/	Fixed, 3		Fixed, 3	
Angle of internal friction, φ_1 (°)	14	18	24	30	14	18
Angle of internal friction, φ_2 (°)	/	/	/	/	22	28

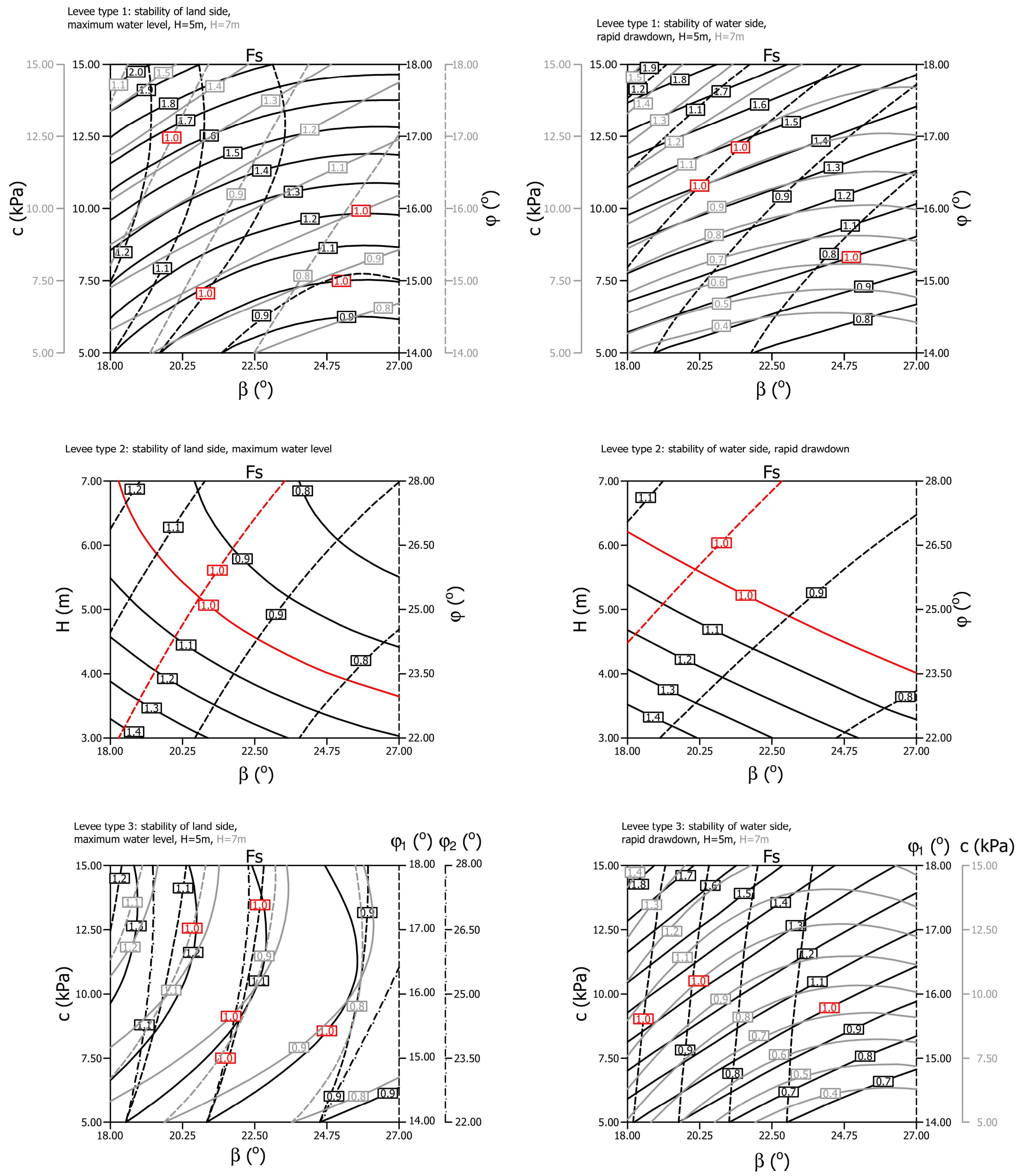

Figure 15. *Structural stability diagrams for analyzed types of levee and different case studies*

Filtration stability

In order to derive filtration stability diagrams (the analyzed case is shown in Figure 14) the experimental design was also set up using Box-Behnken approach, where the output parameter is given as the ratio of the critical exit gradient and the measured exit gradient (exit gradient was determined as an average value of exit gradient from slope foot to 10m to the land side). Calculation of filtration stability was done using finite element analysis. Critical exit gradient depends on the uniformity coefficient Cu of the underlaying layer: $i_{critical}$ =0.4, for Cu=0-10, $i_{critical}$ =0.3 for Cu=10-20 and $i_{critical}$=0.2 for Cu>20. Results of the conducted analyzes are shown in a form of stability diagram, Figure 16 (right). One should note that exit hydraulic gradient was taken as an average value of the exit gradient at the horizontal land side of the levee, from levee toe up 10 m towards the protected area. As result of the conducted analyzes, we derived expressions for safety factor against the filtration instability (defined as $i_{measured}/i_{critical}$) as nonlinear function of hydraulic conductivity of the underlaying layer K_f (m/s) and thickness of the underlaying layer, d (m). Illustrative example of such equation is given below:

$$Fs = -0.19 + 0.56 \cdot d + 6377.6 \cdot K_f - 0.12 \cdot C_u - 411.7 \cdot d \cdot K_f + 0.05 \cdot d \cdot C_u + 15.34 \cdot K_f \cdot C_u - 0.12 \cdot d^2 - 0.0000015 \cdot K_f^2 + 0.0014 \cdot C_u^2, \ \ldots\ \text{for } C_u\text{=0-10, } R^2\text{=0.99, RMSE=0.028} \quad (6)$$

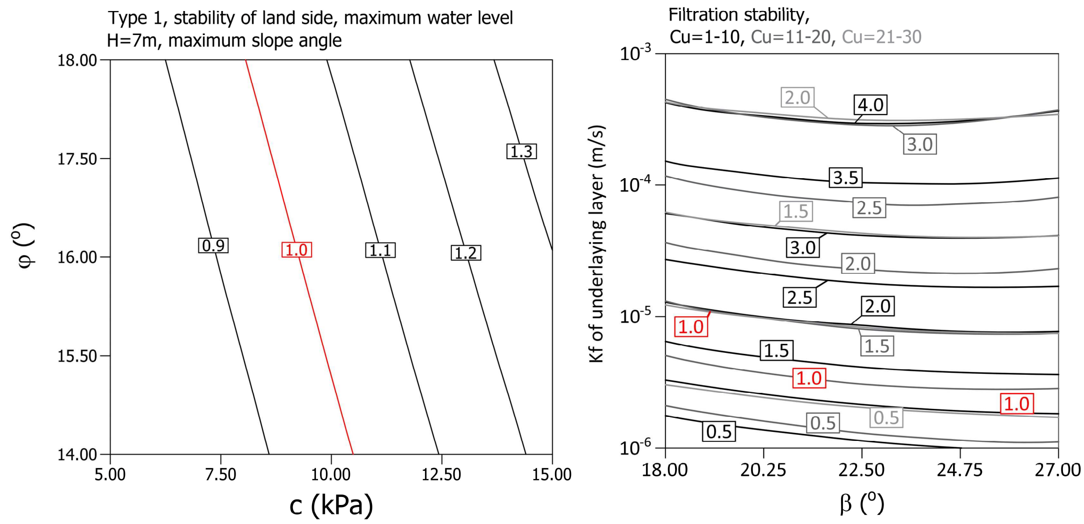

***Figure 16.** Structural stability diagram Fs=f(c,φ) (left) and filtration stability diagram (right)*

CONCLUSIONS

In present paper, we examine the possibility to estimate the composition, compressibility state and stability of existing levees based solely on the results of terrain geoelectric measurements. Question of properties of existing levees is up-to-date and tackles the daily problem of engineering activity, especially concerning the lack of documentation on previous investigation works, design and actual construction and the different hydrological-hydraulic properties connected to climate change. In that sense, results of presented research tend to define the non-invasive approach which will enable reliable assessment of levee properties.

As stated in the introduction, we follow the six main principles:

- maximum reliance on the results of previous investigation works in similar geological environments (maximum use of previous results),
- maximum reduction of invasive investigation works (minimum invasivity),
- maximum use of non-invasive investigation works, including geophysics, CPT and DPSH tests (maximum non-invasivity),
- maximum use of construction and filtration stability analyzes by setting up adequate experimental design (maximum stability analyzes),
- maximum use of statistically significant correlations (statistical significance),
- maximum use of EC-7 and ILH guidance (positive regulatory obedience).

Suggested process flow for the estimation of the composition and state of existing levee could be described as shown in Figure 17.

Regarding the estimation of levee composition and state, results of our analyzes indicate the following:

- there is a statistically significant and physically possible correlations between grain size composition and soil resistivity, i.e., between general coherent/incoherent fraction and sand/gravel percentage when incoherent fraction prevails,
- statistically significant and physically possible correlation could be also established between cone penetration resistance (and corresponding compressibility modulus) and soil resistivity.

Regarding the structural stability of the existing levee, based on the previous investigation works conducted by JCWI, we analyzed the following types of levees:

- Type 1 - levees composed of cohesive materials (silt and clay)
- Type 2 - levees composed of cohesionless material (sand and gravel)
- Type 3 - levees composed of mixed cohesive and cohesionless material.

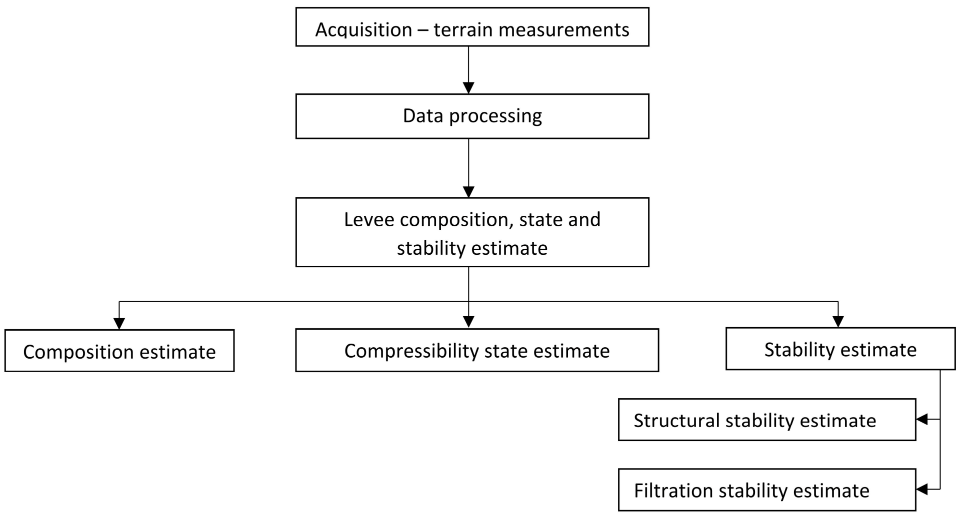

Figure 17. *Algorithm for the assessment of composition, state and stability of the existing levee*

For each levee type, we analyzed two extreme cases: maximum river water level (stability of the land side) and rapid drawdown (stability of the water side). For each type and case, we constructed separate stability diagrams, which could be used as a first step in estimation of levee structural stability. As for the filtration stability, we analyzed a single case of coherent impermeable levee, where the thickness and permeability of underlaying layer was varied. A corresponding filtration stability diagram was also constructed.

Results presented in this paper indicate the following:

- There is a possibility to establish positive, statistically significant, and physically possible correlations between the geophysical research results and other investigation methods. Since geophysical terrain measurements are non-invasive and time-preserving, one needs to force the application of geophysical methods as the primary technique for field measurements, while at the same time continuously developing the correlation with the results of other investigation works,
- Based on the results of numerous stability calculations, one could establish a reliable stability diagram for certain levee types, which could further serve for quick and first assessment of levee stability.

Further research on this topic should include more data (especially from CPT, SPT and DSPH tests), and, if possible, correlation with refractive measurements, including the results of MASW. Also, analyzes of filtration stability should be expanded to cases when permeability of levee itself is also high and there is a possibility to establish a flow through the levee body.

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CONTEMPORARY WATER MANAGEMENT: CHALLENGES AND RESEARCH DIRECTIONS

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„J.ЧЕРНИ"

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PREFACE

Institute of Hydrology was established in 1947 within the Serbian Academy of Sciences. The Hydraulics Laboratory was established that same year within the Federal Ministry of Electricity, a predecessor of the later Hydropower Institute created in 1950. These two institutions were soon merged under the auspices of the Serbian Academy of Sciences into the Hydrotechnical Institute Eng. Jaroslav Černi. This Institute merged with the Serbian Water Management Institute in 1959 to create today's Jaroslav Černi Water Institute.

Over the past decades, the Institute has been the backbone of scientific research in the field of water in Serbia and the former Yugoslavia. The international scientific conference Contemporary Water Management: Challenges and Research Directions is organized to celebrate 75 years of the Institute's long and successful history. The Scientific Board selected 26 papers to provide readers with the best view of the current research results, as well as the further scientific research directions and potential challenges in the future. Selected papers are classified into six conference topics according to the corresponding research field, although one should note that most of the presented works is multidisciplinary, which is after all a characteristic of a modern problem-solving approach in the field of water. Hence, the chosen conference topics and corresponding papers represent only one possible way of classification of the presented works.

We wish to express our gratitude to the International Scientific Board and the Organizing Committee of this international conference for their efforts in selecting the papers, reviewing, and organizing the conference. We also wish to express our gratitude to all the authors of selected papers for the time they spent presenting the results of their research in a way suitable for this conference, and for contributing to the celebration of 75 years since the establishment of the Jaroslav Černi Water Institute. Respecting the importance of jubilee and wishing to express gratitude to previous generations of scientific workers, the Honorary Committee was also formed.

Following the path of previous generations, the Institute's present and future staff remain privileged, and under duty and obligation to continue and improve the scientific and research work of the Institute in the years and decades to come.

Belgrade, October 2022

Editors

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