Theoretical Basis for Designing Seepage-Control Walls in Dam Foundations

M P Sainov
1

1Moscow State University of Civil Engineering (National Research University), Moscow, Russia

E-mail: mp_sainov@mail.ru

Abstract. The structures arranged using the method of «slurry trench cutoff wall» or using secant piles are frequently used as seepage-control elements in dam foundations. However, they are designed based on empirical approaches without theoretical validation. With the aid of theoretical modeling the author revealed main specific features of seepage-control walls stress-strain state. They work not only for cross bending but also are subject to bending in their own plane, as well as they perceive considerable vertical forces. These forces appear due to friction between the wall and soil. The author obtained empirical formulae which at preliminary design stages permit predicting maximum values of compressive stresses in the wall at the moment when vertical forces have maximum values. The study made it possible to verify the recommendations for selection of material for arrangement of seepage-control walls. As a rule, deformation modulus of the wall material should not exceed the deformation modulus of the weakest soil by more than two times. Clay-cement concrete or plastic concrete is recommended to be used for the wall material. Its compressive strength is provided due to lateral compression of the wall by lateral compression of soil and groundwater pressure. For not deep «hanging» walls it is possible to use concrete. The assessment was given of foundation deformation impact on the stress-strain state of seepage-control walls. Occurrence of weak interlayers in the foundation causes in the wall appearance of zones concentrating compressive stresses and additional bending deformations. In high dam foundations there is a danger of sharp decrease of the wall compression pressure due to deformations of the foundation lateral expansion. It is not recommended to use the cantilever pattern of the wall conjugation with the dam body, but arrange a concrete gallery above the wall head. Conjugation by a cantilever is possible only for the walls arranged at the edge of the dam profile.

1. Introduction
The structures arranged with the aid of the method of «slurry trench cutoff wall» or by secant piles are frequently used as seepage-control elements in dam foundations and embankment dam bodies. For example, in the foundation of Karkheh high dam in Iran there is a seepage-control wall (SCW) which occupies the largest in the word area (150000 thou.m²) [1-3]. In China SCWs are arranged in foundations at more than 20 dams [4]. A long SCW was provided in the foundation and the dam body of Merowe HPP in Sudan [5]. At Kureika HPP the diaphragm of bore piles was fulfilled for recovery of the dam water tightness after appearance of a crack in the loam core [6]. In 2017 in Nizhnyaya Bureya HPP dam the diaphragm of bore piles was fulfilled as the main seepage-control element.
However, often SCW is designed with use of empirical approaches based on theoretical understanding of their work and on the results of certain studies. Sometimes it is considered that SCWs work for bending, therefore, danger comes from tensile stresses at bending deformations. In Proceedings of International Commission on Large Dams (ICOLD, 1985, Filling materials for watertight cut-off walls) it is recommended for arranging seepage-control walls (SCW) to use the material, whose deformation modulus is 5 times as much as deformation modulus of the surrounding soil.

To meet this condition SCW is often made of not conventional concrete but of plastic concrete (i.e. concrete including bentonite) or clay-cement concrete (concrete containing more bentonite than cement). In designing it is supposed that closeness of the wall material and surrounding soil deformations will permit for SCW to assume considerable deformations peculiar for foundation soils without loss of strength. Besides, the advantage of clay-cement concrete is its ability of autogenous healing of cracks [7].

For Karkheh dam SCW the plastic concrete was used with deformation modulus 0.7÷2.5 GPa [1]. In [3] it is stressed that such material is suitable in these conditions because the foundation soil, i.e. conglomerate, has deformation modulus equaling to 5÷23 GPa. At Merowe dam the clay-cement concrete was used with deformation modulus 200 MPa [5]. In China for SCW there were used concrete, plastic concrete and clay-cement concrete [4].

For validation of using plastic concretes, clay-cement concretes in dam structures a number of researches experimentally studied their strength and deformation properties [8-12]. By varying the content of cement and bentonite it is possible to reach different values of clay-cement concrete strength and deformation.

For theoretical validation of SCW structures the studies are conducted of their stress-strain state (SSS). A number of works are devoted to this issue [13-21]. They permitted establishing that SCW in dam foundations work not only for bending.

Already in 1976 at operation of Manicougan 3 dam (Canada) it was revealed that SCW made in alluvial foundation is subject to considerable compression in vertical direction, whose value is greater than the dam weight [13]. A hypothesis was made that this compression is caused by friction forces on the wall lateral surfaces.

The effect of appearance in SCW considerable vertical compressive forces was later confirmed by other researchers with the aid of numerical modeling. Thus, in 2000 the author obtained this result applicable to conditions of Yumaguza dam project (Russia). In 2002 the effect of dam compression was established in studies of SCW SSS for Cyprian dam Arminou [14]. This effect was also confirmed in researches [15-21]. Ding et al [18] established that occurrence in the foundation of soft soil interlayers may cause considerable concentration of stresses in certain zones of SCW.

A number of researches deal with selection of approaches providing more favorable SCW SSS. In 2011 Mou et al conducted studies on revealing the impact of the wall material modulus of deformation on its SSS [16]. They established that there is some critical value of deformation modulus at whose increase the stresses in the wall sharply increase. In 2016 Liu et al [20] recommended to use a cantilever pattern of the wall conjugation with the dam body to decrease stresses concentration. A similar recommendation was given by the author in 2001.

However, no unified theory of SCW performance has been developed yet. The fullest analysis of SCW working conditions in embankment dam foundations was fulfilled by Lifeng Wen et al in 2018 [4]. This work contains information about field observations over SSS of a number of SCWs mainly at the dams in China. This data describes not only wall displacements but also stresses in it. In [4] it is shown that SCW conditions greatly differ depending on its location. SCW is subject to considerable compressive stresses when it is located in the middle part of the dam. If SCW is located at the edge of the dam profile this does not happen. The similar result was obtained by the author in 2016 applicable to the dam with combined seepage-control element [22].

In order to create a complete theoretical basis of SCW designing, to reveal impact of SCW SSS different factors, the author conducted a number of investigations [19,21].
2. Methods
The studies were conducted with the aid of numerical modeling by the finite element method. The software program Nds_N developed by the author was used. It permits conducting SSS analysis of embankment dams with consideration of their construction sequence and loading as well as non-linearity of medium behavior.

At modeling the non-linear character of soil deformation the program permits consideration of deformation difference at trajectories of active loading and unloading, decrease of deformation at increase of lateral compression and its increase when approaching the limit state, as well as possibility of material fracture failure at loss of tensile strength. However, at study of SCW SSS the deformation modulus of foundation soils for active loading was assumed to be constant.

At modeling non-linearity of contact interaction there was considered the possibility of loss of contact shear strength and tensile strength. As in other studies [16,18] for modeling of friction at the contact between the wall and soil there were used contact finite elements (Goodman elements). Mohr-Coulomb model was used for determination of shear strength of contacts.

The advantage of using the software program is in the fact that it permits application of high-order elements at finite-element discretization of structures, as well as proper conjugation of elements of different orders. This permitted providing smooth character of stress distribution in a rigid thin-wall structure and therefore, adequate obtained solutions. The specific feature of studies fulfilled by the author is due to the fact that analysis was conducted not only for conditions of a particular structure but also for a wide range of possible alternatives and factors. This permitted not only determining specific features of SCW SSS but formulation of recommendations for its regulation.

The important component of SCW analysis methodology is consideration of effect of enhancing clay-cement concrete compressive strength (plastic concrete) at lateral compression. Mohr-Coulomb strength theory was used for determination of material strength with consideration of compression:

\[ R = R_1 + \sigma_1 (1 + \sin \varphi) / (1 - \sin \varphi) \]  
(1)

where \( R_1 \) – uniaxial compressive strength of material;  
\( \sigma_1 \) – compression stress (maximum principal stress);  
\( \varphi \) – material angle of internal friction.

For approximate prediction of uniaxial compressive strength \( R_1 \) of clay-cement concrete the author fulfilled processing of the results of tests carried out by A.V. Radzinsky [10]. The following relationship between uniaxial compressive strength \( R_1 \) (MPa) and modulus of linear deformation \( E \) (MPa) was obtained

\[ R_1 = 0.29 \times E^{0.32} \]  
(2)

3. Results and discussion
For revealing main specific features of SCW SSS in the dam foundation the author fulfilled methodical study described in [21]. The considered wall was made in the foundation of a 100 m high earth-rockfill dam. In the study the assessment was made of SCW SSS depending on the following factors: ratio between deformation moduli of the wall and soil, depth and conditions of the wall resting. Two alternatives of the wall resting were considered: a wall resting on strong foundation (i.e. standing wall) and a hanging wall.

The study permitted learning how SCW SSS is formed. If the wall material deformation modulus \( E_{wall} \) slightly differs from soil deformation modulus \( E_{soil} \) (at \( E_{wall}/E_{soil} < 5 \)) joint deformation of the wall and soil occurs (Figure 1). At \( E_{wall}/E_{soil} > 5 \) at the contact of the wall and soil the considerable tangent stresses appear. They grow with increase of the foundation settlements at the dam construction. Loss of the contact shear strength, as a rule, starts from the upper end of the contact, because at this section the normal stresses are less by value. At loss of shear strength the slippage takes place at the contact. Due to this fact at the remaining sound section of the contact the tangent stresses become even more, due to which compressive stresses are concentrated in a certain section of the wall.

The time moment till the reservoir final impoundment is one on the most dangerous, because at this time moment the wall is subject to maximum compressive longitudinal force.
After the reservoir impoundment and start of seepage flow in the foundation the structure starts to be subject to horizontal displacements and the conditions of SCW performance sharply change. On the upstream contact of the wall (from the upstream side) with soil the compressive normal stresses sharply decrease, therefore, the contact loses its shear strength and slides. Due to friction decrease the longitudinal forces transferred to the wall sharply decrease.

![Settlements (U_y) of the wall and soil:](image)

![Vertical normal stresses (σ_y):](image)

\[
\frac{E_{\text{wall}}}{E_{\text{soil}}} = 1 \quad \rightarrow \quad \frac{E_{\text{wall}}}{E_{\text{soil}}} \approx 5 \quad \rightarrow \quad \frac{E_{\text{wall}}}{E_{\text{soil}}} \approx 10 \quad \rightarrow \quad \frac{E_{\text{wall}}}{E_{\text{soil}}} \approx 50 \quad \rightarrow \quad \frac{E_{\text{wall}}}{E_{\text{soil}}} > 100
\]

**Figure 1.** Variation of curves shapes of settlements and vertical stresses in the wall depending on the ratio of deformation moduli of the wall material and the surrounding soil.

The curve of soil settlement is shown by a dashed line.

With this point of view the second time moment, when the dam and SCW apart from loads from the weight is subject to loads from hydrostatic pressure and seepage forces, is less dangerous for SCW at \(\frac{E_{\text{wall}}}{E_{\text{soil}}} < 10\). Moreover, due to wall compression by water pressure the compressive strength of clay-cement concrete (plastic concrete) and safety factor increase.

For rigid walls the second time moment is the most dangerous because non-uniform distribution of horizontal displacements leads to the wall bend. Bending deformations may cause tensile stresses in a rigid wall.

The carried out studies permitted giving scientific justification of the recommendations for selection of material for seepage-control walls. For this wide range of ratio \(\frac{E_{\text{wall}}}{E_{\text{soil}}}\) the comparison was made between the maximum value of compressive stresses in the wall and its strength in the most dangerous sections. Schematically the shape of corresponding curves is given in Fig. 2.

Relationship between maximum values of compressive stresses \(\sigma_{\text{max}}\) and \(\frac{E_{\text{wall}}}{E_{\text{soil}}}\) has a complicated character.

At the initial section of curve 1 (Figure 2), i.e. at \(\frac{E_{\text{wall}}}{E_{\text{soil}}} < 20\) there observed intensive growth of \(\sigma_{\text{max}}\) at increase of \(\frac{E_{\text{wall}}}{E_{\text{soil}}}\). The author suggested describing by power law dependence which may be used at preliminary stages of designing

\[
\sigma_{\text{max}} = A \, p \left( \frac{E_{\text{wall}}}{E_{\text{soil}}} \right)^n
\]

Here \(A, n\) – empirical indices;

\(p\) – pressure transferred by the dam to the foundation.

Power index \(n\) is less than 1; its value depends on the wall depth and the dam height. Value \(A\), as a rule, is equal to 1, but it may be more than 1, if the wall is conjugated with the dam in a form of cantilever.
Figure 2. Variation curve of maximum values of wall compressive stresses (curve 1) and material compressive strength (curve 2) depending on the ratio of the wall and soil deformation moduli.

At $E_{wall}/E_{soil} < 10$ by value $\sigma_{max}$ the impact of other factors beside $E_{wall}/E_{soil}$ is small. Namely, value $\sigma_{max}$ has small dependence from the wall thickness. This is explained by the fact that in this particular case the wall rigidity is not great and the wall is deformed jointly with the foundation soil.

Analysis showed that at increase of ratio $E_{wall}/E_{soil}$ the value of maximum stress $\sigma_{max}$ as a rule, grows quicker than clay-cement concrete compressive strength $R$ (Figure 1). Usually the compressive strength condition is met at $E_{wall}/E_{soil} < (2\div5)$. This confirms ICOLD recommendations, but poses more strict requirements to walls material.

At the second section at $E_{wall}/E_{soil} > 20$, the stresses grow slower (Figure 1). This is connected with development of processes of soil sliding against the wall. There is a limit value of compressive stresses in the wall $\sigma_{lim}$. Depending on the conditions the limit of stress growth is reached at $E_{wall}/E_{soil} > (10\div100)$.

For description of the stresses variation in the whole interval of values $E_{wall}/E_{soil}$ the author suggested the following approximation

$$\sigma_{max} = B \cdot \frac{p \cdot E_{wall}}{[(B/A-1) \cdot E_{soil} + E_{wall}]}$$

(4)

Value $B$ in this formula is the limiting value of compressive stresses in the wall $\sigma_{lim}$.

Value $\sigma_{lim}$ depends on several factors: conditions of the wall resting, the wall depth and thickness, as well as the contact shear parameters. In the wall resting on rock foundation the compressive stresses reach greater values than those in the hanging walls. The author developed a theoretical formula which permits determining value $\sigma_{lim}$ by calculations:

$$\sigma_{lim} = p + \frac{h/t}{2p \cdot \lambda \cdot \tan \varphi + 2c + \gamma \cdot \lambda \cdot h \cdot \tan \varphi},$$

(5)

where $\varphi$, $c$ – angle of internal friction and specific cohesion at the contact of the wall and soil;

$\gamma$ – specific weight of foundation soil;

$\lambda$ – coefficient of soil lateral pressure;

$h$ – wall depth in the design section;

$t$ – wall thickness.

It is seen from the formula that the more is the wall depth the higher is $\sigma_{lim}$ and, correspondingly, $\sigma_{max}$. However, this formula does not permit making precise predictions. This is connected with complexity in determining the value of lateral pressure coefficient $\lambda$, on which the contact shear strength depends. It was revealed that under the action of the dam weight the foundation is expanded laterally, which decreases soil lateral pressure on the wall; it is less than stand-by pressure. This sharply decreases value $\sigma_{lim}$.

Due to existence of limit in growth of compressive stresses $\sigma_{lim}$ at high values of $E_{wall}/E_{soil}$ the strength of not deep hanging walls may be provided even at using concrete (Fig.1). This conclusion differs from ICOLD recommendations, but is confirmed by experience in operation of concrete SCWs, which were arranged at several high concrete face rockfill dams [4].

The most unfavorable SSS is peculiar to deep SCW resting on rock foundation. Decrease of SCW compressive stresses is possible by increase of its thickness but it is unreasonable. In the wall of large
thickness there is a higher risk of appearance of considerable tensile stresses due to bending deformations.

Rigid walls embedded in strong rock foundation also perform in unfavorable conditions. Considerable bending deformations at the place of embedment lead to appearance of tensile stresses; probability of cracking in these walls is the highest. It is not recommended to use concrete in such walls.

Given above recommendations refer to conditions of homogeneous structure of foundation. The studies revealed that heterogeneous structure of foundation considerably complicates conditions of SCW performance. At the sections of compressed interlayers in SCW considerable compressive stresses are concentrated. Besides, at perceiving horizontal forces at the boundaries of layers with various deformability considerable bending deformations appear, which increases the risk of tensile strength loss. The author established that for providing strength it is necessary to meet condition \( E_{\text{wall}} / E_{\text{soil}} < 2 \). At that, value of \( E_{\text{soil}} \) should be determined from the weakest soil. Taking this fact into account, in Karkheh SCW the real value of ratio \( E_{\text{wall}} / E_{\text{soil}} \) could reach 50. Evidently it was one of possible reasons why arrangement of an additional wall was required at Karkheh dam [3].

To performance in conditions of heterogeneous structure of soil mass there may be attributed the performance of high thin cantilevers with the aid of which at a number of dams (Karkheh, Xianlongdi) the SCWs were conjugated with the dam body. If the dam soil is more deformable as compared to that of the foundation soil, the cantilever SSS is unfavorable. At dam settlements the cantilever may concentrate high compressive forces, and at dam horizontal displacements considerable bending deformations may appear in it. Analysis showed that there is a high probability of cracking in the cantilever. Therefore, it is recommended to conjugate the wall with the dam body with the aid of movable connection when a concrete gallery is arranged above the wall head. The researches in [20] arrived to such conclusions. The cantilever pattern may be used only in cases when the dam body and foundation soil are close by deformation properties and the wall is arranged at the edge of the dam profile.

Separate study was conducted for assessment of impact on conditions of SCW SSS formation of the effect of bentonite crust formation. The methodology of «slurry trench cutoff wall» envisages that the wall is concreted by the method underwater concreting under protection of bentonite slurry. After filling the trench with bentonite slurry a bentonite crust is left on the edges of the trench [23]. This crust has lower parameters of shear strength. According to the data of Belarusian researches the crust of the angle of internal friction is estimated equal to 20°, specific cohesion – 20 kPa.

The author also conducted studies of 3D SCW SSS. A number of authors by conducting studies [4] revealed that the danger is presented by the section conjugating the wall with rock foundation; tensile stresses may appear there.

However, the author in [22] revealed one more peculiarity of SCW SSS in 3D conditions. This is existence of the wall bend in its own plane. It appears not only due to SCW displacements in direction from one side to the other, but also due to the wall non-uniform settlements along the section line. The result of this bend may be formation of the zone of tensile stresses in direction from one side to the other.

4. Conclusions
1. Seepage-control walls made in the dam foundation perform in complicated conditions: they perceive not only seepage water pressure but also considerable vertical loads caused by foundation deformations under the dam weight. The walls are subject to not only bending moment and transversal force, but also a longitudinal force. The wall is also subject to bending in its own plane.

2. Stress-strain state of a seepage-control wall to a considerable extent is determined by the difference between material deformation and deformation of the surrounding soil. If a very rigid material is selected for the wall, then due to high deformations characterizing soil mass there is an increased threat of loss of the wall tensile and compression strength. By the results of study the danger of strength loss appears even if the wall material deformation modulus is only 5 times as much as the
soil modulus of linear deformation. Taking into account the heterogeneous structure of the foundation and variability of soil and wall properties, it may be recommended to use the material, whose deformation modulus is not more than 2 times as much as the soil deformation modulus. As a rule, plastic concrete or clay-cement concrete should be used for wall construction, however, in some cases it is possible to make seepage-control walls of concrete. The advantage of clay-cement concrete is that in conditions of the wall compression by lateral pressure of soil and groundwater its compressive strength considerably increases.

3. The author suggested empirical formulae which permit at initial design stages to predict maximum value of compressive stresses in the seepage-control wall.

4. The study was fulfilled on revealing impacts of different factors on stress-strain state of seepage-control walls. It was revealed that due to increase of the wall thickness it is not possible to reach significant improvement of its SSS.

References
[1] Mirghasemi A A, Pakzad M, Shadravan B 2005 The world’s largest cutoff wall at Karkheh dam International Journal on Hydropower and Dams 12(2) 2–6
[2] Shadravan B, Mirghasemi A A, Pakzad M 2004 Karkheh Storage Dam Cutoff Wall Analysis and Design International Conference on Case Histories in Geotechnical Engineering http://scholarsmine.mst.edu/icchge/5icchge/session02/40
[3] Heidarzadeh M, Mirghasemi A A, Niroomand H, Eslamin F 2018 Construction and performance of the Karkheh dam complementary cut-off wall: an innovative engineering solution International Journal of Civil Engineering 17(6) 859–869
[4] Wen L, Chai J, Xu Z, Qin Y, Li Y 2018 A statistical analysis on concrete cut-off wall behaviour Proceedings of the Institution of Civil Engineers: Geotechnical Engineering 171(2) 160–173
[5] Ehhardt T, Scheid Y, El Tayeb A 2011 Design and construction of the rockfill dams and the cut-off wall at the Merowe Project WasserWirtschaft 101(1–2) 36–42
[6] Malyshev L I, Shishov I N, Kudrin L P, Bardyukov V G 2001 Technical decisions of results of works on construction of the antifiltration wall in the Kureya HPP dam base Gidrotekhnichesko Stroit'estvo 3 31–36
[7] Solsky S V, Orlova N L, Velichko A S 2018 Crack self-healing in clay-cement concrete diaphragm of embankment dam Magazine of Civil Engineering 1 3–12
[8] Hinchberger S, Weck J, Newson T 2010 Mechanical and hydraulic characterization of plastic concrete for seepage cut-off walls Canadian Geotechnical Journal 47(4) 461–471
[9] Pisheh Y P, Mir Mohammad Hosseini S M 2012 Stress-strain behavior of plastic concrete using monotonic triaxial compression tests Journal of Central South University of Technology (English Edition) 19(4) 1125–1131
[10] Rasskazov L N, Radzinskiy A V, Sainov M P 2014 Selection of the Composition of Clay-Cement Concrete for Construction of “Walls-in-the-Ground” Power Technology and Engineering 48(3) 167–173
[11] Rasskazov L N, Radzinskiy A V, Sainov M P 2015 Strength and Deformability of Clay-cement Concrete in Complex Stress State Power Technology and Engineering 48(5) 361–365
[12] Pisheh Y P, Hosseini M M 2019 Experimental investigation of mechanical behavior of plastic concrete in cutoff walls Journal of Materials in Civil Engineering 31(1) 04018355
[13] Dascal O 1979 Structural behavior of the Manicougan 3 cutoff Canadian Geotechnical Journal 16(1) 200–221
[14] Brown A J, Bruggemann D A 2002 Arminou Dam, Cyprus, and construction joints in diaphragm cut-off walls Geotechnique 52(1) 3–13
[15] Xiong H, Wang Q, Gao X, Zhou W, Gao M 2010 Stress deformation analysis of plastic concrete cutoff wall for the first stage cofferdam of Shawan hydropower station Journal of Hydroelectric Engineering 29(2) 197–203+189
[16] Mou R, Xu C-J, Ma X-H 2012 Analysis on stress and deformation of low elastic modulus concrete cutoff wall inside the dam body Applied Mechanics and Materials 130-134 3208–3215
[17] Gao J, Chen Y 2012 Study on stress of closed cut-off wall in earth-rock dam reinforcement under different engineering conditions Advanced Materials Research 594-597 1969-1974
[18] Ding Y H, Zhang Q G, Zhang B Y 2013 FEM analysis of stress deformation characteristics of cut-off walls in high core rockfill dam. Shuili Fadian Xuebao Journal of Hydroelectric Engineering 32(3) 162-167
[19] Sainov M P 2015 3D performance of a seepage control wall in dam and foundation Magazine of Civil Engineering 57(5) 20–33+100–101
[20] Liu S-H, Wang L-J, Wang Z-J, Bauer E 2016 Numerical stress-deformation analysis of cut-off wall in clay-core rockfill dam on thick overburden Water Science and Engineering 9(3) 219–226
[21] Sainov M P, Lubyanov L V 2017 Stress-strain state of seepage-control walls in foundations of embankment dams Magazine of Civil Engineering 73(5) 96–112
[22] Sainov M P 2016 Analysis of normal operation of a rockfill dam with combination of seepage-control elements: reinforced concrete face and a clay-cement-concrete wall Magazine of Civil Engineering 64(4) 3–9
[23] Soroush A, Soroush M 2005 Parameters affecting the thickness of bentonite cake in cutoff wall construction: Case study and physical modeling Canadian Geotechnical Journal 42(2) 646-654