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Manuscript title: Evaluation of concrete and geomembrane lining options for a canal in Egypt

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Abstract

This technical note complements a published lining evaluation for a canal in Egypt. Concrete and geomembrane linings are compared regarding leakage control and cost. Published data on leakage with concrete and geomembrane linings are reviewed, and analyses show that the predicted leakage rate is significantly lower with a geomembrane lining than with a concrete lining. The findings presented herein on leakage control and cost are significantly different from the findings of the published lining evaluation.

Keywords: Geosynthetics; geomembrane; lining; concrete; canal; leakage; cost

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1 Introduction

A paper published by Elkamhawy *et al*. (2021) presents a lining evaluation for the Ismailia Canal in Egypt. This lining evaluation compares different types of linings regarding leakage control and cost, in particular concrete linings and geomembrane linings. This technical note complements the lining evaluation for the Ismailia Canal. Considering the size of this canal, the lessons learned from the discussions presented herein are applicable to all medium- to large-sized canals, regardless of their location.

The paper by Elkamhawy *et al*. (2021) shows that lining canals is beneficial to water conservation, which is important at a time when water conservation is a high priority and many canals in the world need to be rehabilitated. However, two issues in the paper by Elkamhawy *et al*. (2021) have prompted the preparation of this technical note: (1) the hydraulic conductivities, used for the published lining evaluation, are not representative of the properties of concrete and geomembranes, which leads to incorrect evaluation of the leakage rates; and (2) several of the cross sections used for the cost evaluation of the lining options are not consistent with the state of practice, which leads to incorrect cost comparison. These two issues are addressed in this technical note. Hereafter, three sections are devoted to leakage issues (Sections 2 to 4) and one section is devoted to the cost of lining systems (Section 5).

2 Rate of leakage through concrete lining

2.1 Hydraulic conductivity of concrete used in the published lining evaluation

A hydraulic conductivity of 4.63 x 10^{-14} m/s is used for concrete in the paper by Elkamhawy *et al*. (2021). This hydraulic conductivity is equal to 4 x 10^{-9} m/day. It should be noted that a hydraulic conductivity of 4 x 10^{-9} m/day is mentioned in Table 1, page 13, of a paper by Abd-Elhamid *et al*. (2019), which is cited in the paper by Elkamhawy *et al*. (2021). This presumably indicates that Elkamhawy *et al*. (2021) used for the hydraulic conductivity of concrete the value published earlier by Abd-Elhamid *et al*. (2019). Also, it appears to be implied in the paper by Abd-Elhamid *et al*. (2019) that a paper by Schneider *et al*. (2012) was the source for the above hydraulic conductivity for concrete. This was confirmed by a personal communication from Abd-Elaty (2021), who is co-author of both Abd-Elhamid *et al*. (2019) and Elkamhawy *et al*. (2021).

Although Schneider *et al*. (2012) do not give 4.63 x 10^{-14} m/s (4 x 10^{-9} m/day), they mention low hydraulic conductivities, specifically 5.67 x 10^{-13} m/s and 5.87 x 10^{-14} m/s for concrete and mortar, respectively. The actual wording used by Schneider *et al*. (2012) is noteworthy: they state that “the estimated hydraulic conductivity is 5.67 x 10^{-13} m/s and 5.87 x 10^{-14} m/s for concrete and mortar, respectively”.

It is important to note that Schneider *et al*. (2012) indicate that these low values are only “estimated” hydraulic conductivities. Indeed, the values mentioned by Schneider *et al*. (2012) were estimated on the basis of measurements on unsaturated flow. Since they were not obtained from measurements on saturated flow (i.e. flow of water in concrete saturated with water), they are not representative of the permeability of concrete linings in canals where concrete is saturated with water when the canal is in service. Estimating hydraulic conductivity from measurements on unsaturated flow requires a complex analysis with simplifying assumptions. Olchitzky (2002) showed that hydraulic conductivities of concrete

estimated from measurements on unsaturated flow can be underestimated by a factor 10^3. In other words, an estimated hydraulic conductivity of 10^{-14} m/s may be, in fact, 10^{-11} m/s.
The above discussion shows that the hydraulic conductivity of 4.63 x 10^{-14} m/s (used for concrete in the paper by Elkamhawy *et al*. 2021) is not representative of the hydraulic conductivity of concrete linings in canals.

2.2 Published data on the hydraulic conductivity of concrete

It is well known that the hydraulic conductivity of the type of concrete used in civil engineering structures exposed to saturated flow of water, such as canal linings, is at best of the order of 1 x 10^{-12} m/s in the case of a concrete specimen in perfect condition (e.g. a homogeneous specimen of concrete without cracks or joints). Values of the order of 10^{-12} m/s can be found in numerous publications, where the hydraulic conductivity of concrete was obtained from measurements on saturated flow, such as Charron *et al*. (2008), Gérard (1996), Jemimah Carmichae & Prince Arulraj (2017), Villar *et al*. (2012) and Zhang *et al*. (2020). Higher hydraulic conductivity values have also been published for concrete in perfect condition. Thus, some publications, such as Aldea *et al*. (1999), Desmettre (2012) and Picandet (2001), conclude that the hydraulic conductivity of concrete in perfect condition is of the order of 10^{-11} m/s. Clearly, 1 x 10^{-12} m/s is the lowest hydraulic conductivity actually measured in the case of saturated flow through specimens of concrete in perfect condition (with the possible exception of special types of concrete, which are not used for canal linings).

2.3 Hydraulic conductivity of concrete in service

The perfect condition mentioned above exists only in laboratory specimens. In the field, minor cracks are always present in concrete, even shortly after lining construction. As a result, the hydraulic conductivity of concrete in the field is higher than the 10^{-11} m/s or 10^{-12} m/s mentioned above in Section 2.2. In the case of concrete with minor cracks, hydraulic conductivities between 1 x 10^{-10} m/s and 1 x 10^{-8} m/s were measured by Aldea *et al*. (1999), Charron *et al*. (2008), Chen (2011), Desmettre (2012), Desmettre and Charron (2012), Gérard (1996) and Hubert *et al*. (2015).
The minor cracks mentioned above result essentially from shrinkage due to the curing of concrete shortly after its placement. More cracking occurs in the field when a concrete lining is subjected to stresses, in particular as a result of displacement of the supporting soil. Hydraulic conductivities of the order of 10^{-7} m/s, even 10^{-6} m/s, were obtained on concrete samples subjected to stresses in the laboratory that simulate stresses in the field (Desmettre 2012, Gérard 1996 and Hubert *et al*. 2015). Furthermore, leakage due to construction and expansion joints that exist between concrete panels in the field is not considered in the tests reported in the publications mentioned above. This type of leakage through concrete linings can be significant. Finally, a much higher rate of leakage would characterize concrete having undergone some deterioration in the field, which may happen a few years after construction (see Section 2.2.5 of Giroud and Plusquellec 2017).

2.4 State of practice

According to the state of practice, leakage rates of 25 to 50 mm/day are typically considered for a canal concrete lining properly constructed and maintained in good condition (see Section 2.4.3 of Giroud and Plusquellec 2017). In the case of the Ismailia Canal, the average water depth is 4.4 m (considering the bottom of the canal and the portion of the side slopes of the canal below the average water surface). This average water depth gives a hydraulic gradient of 44 in the case of a typical 0.1 m thick concrete lining. Using Darcy's equation with this hydraulic gradient shows that leakage rates of 25 to 50 mm/day (i.e. 2.9 to 5.8 x 10^{-7} m/s) correspond to a concrete hydraulic conductivity of 6.6 x 10^{-9} m/s to 1.3 x 10^{-8} m/s. These values are in good agreement with the values of the order of 10^{-8} m/s obtained experimentally for cracked concrete, as indicated above in Section 2.3.

2.5 Application to the Ismailia Canal

If a hydraulic conductivity of 1 x 10^{-8} m/s (as justified above) had been used for the concrete lining in the published lining evaluation for the Ismailia Canal, the calculated leakage rate for a hydraulic gradient of approximately 44 would have been 4.4 x 10^{-7} m/s (i.e. approximately 40 mm/day). These values of hydraulic conductivity and leakage rate would have been consistent with experimental data and the state of practice for a canal concrete lining properly constructed and maintained in good condition.

In comparison with the rationally selected hydraulic conductivity of 1 x 10^{-8} m/s mentioned above, it appears that the hydraulic conductivity of 4.63 x 10^{-14} m/s used by Elkamhawy *et al*. (2021) in the lining evaluation for the Ismailia Canal was underestimated by as much as five orders of magnitude, which is considerable. As a result, the leakage rates calculated for the concrete lining, and presented in the published lining evaluation, were significantly underestimated.

3 Rate of leakage through geomembrane lining

3.1 Hydraulic conductivity of geomembrane used in the published lining evaluation

A hydraulic conductivity of 1.16 x 10^{-10} m/s is used for the geomembrane in the lining evaluation for the Ismailia Canal presented in the paper by Elkamhawy *et al*. (2021). It is likely that this value was derived from a standard test for measuring flux of water through geomembranes such as the test described in the European standard EN 14150. This test is often used with the French norm NF 84-500, which specifies that a geomembrane is acceptable if the water flux through the geomembrane under a water pressure of 100 kPa is less than 1 x 10^{-5} m/day, that is 1.16 x 10^{-10} m/s. As indicated above, this value was used as a geomembrane hydraulic conductivity in the paper by Elkamhawy *et al*. (2021). However, this is a flux under a pressure of 100 kPa, not a hydraulic conductivity. The hydraulic conductivity is the flux divided by the hydraulic gradient. The 100 kPa pressure used in the test is the pressure applied by 10.19 m of water. With a 1 mm thick geomembrane, the hydraulic gradient is 10,190. If Darcy's equation is assumed to be applicable to geomembranes (as it is in the paper by Elkamhawy *et al.* 2021), dividing 1.16 x 10^{-10} m/s by 10,190 gives a hydraulic conductivity of 1.14 x 10^{-14} m/s. Clearly, using a flux value for a hydraulic conductivity resulted in overestimating the hydraulic conductivity by four orders of magnitude. As a result, the leakage rates calculated for the geomembrane lining in the paper by Elkamhawy *et al*. (2021) were significantly overestimated.

3.2 Evaluation of rate of leakage through geomembrane linings

Contrary to the approach used in the paper by Elkamhawy *et al*. (2021), water flow through geomembrane linings is not quantified by Darcy's equation. Water flow through geomembrane linings is the result of leakage through holes. A study, based on theoretical developments and data on actual holes in geomembranes from the monitoring of geomembrane linings in the field (Peggs and Giroud 2014, and Giroud 2016), has led to the conclusion that the leakage rate, q, due to holes that statistically exist in geomembranes installed in accordance with the state of practice can be calculated using the following equation:

$$q = 1150\sqrt{h} \quad \text{wih } q \text{ in lphd and } h \text{ in m} \tag{1}$$

where h is the depth of water on top of the geomembrane and with lphd = liters per hectare per day.

With a different unit for the leakage rate, Equation (1) becomes:

$$q = 1.33 \times 10^{-9}\sqrt{h} \quad \text{wih } q \text{ in m/s and } h \text{ in m} \tag{2}$$

For an average water depth of 4.4 m (as indicated in Section 2.4), the leakage rate through the geomembrane, calculated using Equation (2), is 2.8 x 10^{-9} m/s. This leakage rate does not depend on the geomembrane type and thickness, since it is governed by holes.

Another mode of fluid migration through geomembranes is diffusion at the molecular scale. This mode of fluid migration is effective for organic solvents, but negligible for water. Indeed, according to tests results published by Eloy-Giorni *et al*. (1996), a permeation coefficient of 2.5×10^{-16} m^2/s can be used for water diffusion through a high-density polyethylene geomembrane, hence a flux of 2.5×10^{-13} m/s if the geomembrane is 1 mm thick. This flux is four orders of magnitude lower than the leakage rate due to holes (2.8 x 10^{-9} m/s, as indicated above), which shows that diffusion of water is negligible. Therefore, water migration through holes is the only relevant leakage mechanism in the case of high-density polyethylene geomembranes.

3.3 Equivalent hydraulic conductivity

Even though leakage associated with geomembranes is not governed by Darcy's equation, an equivalent hydraulic conductivity can be derived for the considered geomembrane for the sake of comparison with the lining evaluation approach used by Elkamhawy *et al*. (2021). From the above leakage rate value of 2.8 x 10^{-9} m/s, an equivalent hydraulic conductivity value can be derived for the 1 mm thick geomembrane considered by Elkamhawy *et al*. (2021). Under an average water depth of 4.4 m (as indicated in Section 2.4), this geomembrane would be subjected to a hydraulic gradient of 4400. Therefore, the equivalent hydraulic conductivity is 6.4 x 10^{-13} m/s (i.e. 2.8 x 10^{-9} /4400). It should be noted that this hydraulic conductivity takes into account the number and size of holes that are statistically present in geomembranes installed in accordance with the state of practice. It should also be noted that an equivalent hydraulic conductivity of 6.4 x 10^{-13} m/s is consistent with the state of practice for canal lining. Indeed, as indicated above, it corresponds to a leakage rate of 2.8 x 10^{-9} m/s (i.e. 0.24 mm/day), which is consistent with the leakage rate of less than 1 mm/day often mentioned for a canal geomembrane lining properly installed and maintained in good condition (see Section 2.4.3 of Giroud and Plusquellec 2017).

3.4 Application to the Ismailia Canal

As shown above in Section 3.3, to calculate the rate of leakage through a geomembrane lining in the published lining evaluation for the Ismailia Canal, an equivalent hydraulic conductivity of 6.4×10^{-13} m/s should have been used rather than 1.16×10^{-10} m/s. Thus, the equivalent hydraulic conductivity of the geomembrane lining was overestimated by a factor of approximately 180 in the lining evaluation for the Ismailia Canal by Elkamhawy *et al*. (2021). As a result, the leakage rate through the geomembrane was significantly overestimated.

4 Leakage rate comparison

As indicated above in Sections 2.5 and 3.4, the hydraulic conductivity of the concrete was significantly underestimated and the equivalent hydraulic conductivity of the geomembrane was significantly overestimated in the lining evaluation for the Ismailia Canal by Elkamhawy *et al*. (2021). Consequently, in the results of the Ismailia Canal lining evaluation presented in Table 3 of the paper by Elkamhawy *et al*. (2021), the calculated leakage rate for the geomembrane lining is approximately 1300 times higher than the calculated leakage rate for the concrete lining. However, based on the data presented in this technical note, the predicted rate of leakage through the geomembrane lining (2.8×10^{-9} m/s) is two orders of magnitude lower than the predicted rate of leakage through the concrete lining (4.4×10^{-7} m/s).
Clearly there is a significant difference between the leakage rate comparison presented by Elkamhawy *et al*. (2021) on the basis of incorrect data on the properties of lining materials and the leakage rate comparison presented in this technical note, which is supported by a wealth of experimental data and is consistent with the state of practice.

5 Cost comparison

Section 3.4 of the paper by Elkamhawy *et al*. (2021) presents a comparative cost study of several different lining techniques. The costs related to concrete and geomembrane linings presented in the paper by Elkamhawy *et al*. (2021) are as follows (with thicknesses in parentheses):

- 18.10 $/m^2 for plain concrete (0.1 m) over pitching (i.e. dry stone bedding) (0.3 m);
- 18.05 $/m^2 for plain concrete (0.15 m) over sand-cement (0.2 m);
- 26.00 $/m^2 for reinforced concrete (0.1 m) over sand-cement (0.2 m); and
- 26.40 $/m^2 for geomembrane (1 mm) beneath both sand-cement (0.2 m) and plain concrete (0.2 m).

The above cases show that the cost of the geomembrane solution estimated by Elkamhawy *et al*. (2021) is 46% higher than the estimated cost of the plain concrete solutions.
The purpose of the plain concrete layer placed on top of the geomembrane is only to protect the geomembrane against mechanical damage and exposure to weather and solar radiation. The thickness of this concrete layer (0.2 m) exceeds by far the maximum thickness of plain concrete of 0.1 m suggested in the "Linings for Irrigation Canals" manual by the US Bureau of Reclamation (USBR 1963). In this manual, a thickness greater than 0.1 m is not required for a concrete layer that has no structural and waterproofing function.

With a concrete thickness of 0.1 m and a sand-cement thickness of 0.1 m, the cost of the geomembrane solution becomes 15.5 $/m^2 (i.e. 7.9 $/m^2 for the concrete and 3.1 $/m^2 for the for the sand-cement) which is 14% lower than the 18.05 $/m^2 for the plain concrete linings and 40% lower than the 26 $/m^2 for reinforced concrete linings. The cost of the geomembrane solution would be approximately the same (i.e. 15.5 $/m^2) if the layer of sand-cement were replaced by a geotextile.

On the basis of the realistic thicknesses of materials used above, it appears that, for the Ismailia Canal, the geomembrane solution is 14% less expensive than the two plain concrete solutions considered in the paper by Elkamhawy *et al*. (2021) and 40% less expensive than the reinforced concrete solution. It is acknowledged that the cost of materials and construction varies greatly from one canal to another. However, the lesson learned from the Ismailia Canal cost comparison is applicable to other canals: cost comparisons should be done with realistic configurations.

6 Conclusion

The conclusion of the lining evaluation for the Ismailia Canal presented in the paper by Elkamhawy *et al*. (2021) is that the rate of leakage through a geomembrane lining is approximately three orders of magnitude higher than the rate of leakage through a concrete lining. This conclusion is incorrect because it is based on leakage rates underestimated for concrete and overestimated for the geomembrane, as demonstrated in this technical note. When realistic properties of the lining materials are used, as shown in this technical note, rather than being three orders of magnitude higher than the rate of leakage through a concrete lining, the rate of leakage through a geomembrane lining can be estimated to be two orders of magnitude lower. This conclusion is not limited to the Ismailia Canal: it is applicable to all medium- to large-sized canals, as indicated in Section 1.

The cost comparison presented in this technical note shows that, at the Ismailia Canal, the cost of a geomembrane lining (including appropriate concrete protection) can be estimated to be 14% lower than the cost of a plain concrete lining and 40% lower than the cost of a reinforced concrete lining, whereas the paper by Elkamhawy *et al*. (2021) portrays the geomembrane lining as being 46% more expensive than a plain concrete lining because an unrealistic lining configuration was considered. This cost comparison can serve as an example for other canals.

The information and the discussions presented in this technical note should be useful to design engineers preparing specifications for canal lining and should prevent them from being misled by results derived from improperly selected parameters.

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