The Effects of the Structure—Foundation Interaction in the Structural Response of a TBM Gallery

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Abstract: The effects of the interaction between a gallery lining and surrounding ground are evaluated. The gallery is circular with constant thickness and surrounding ground as geotechnical characteristics is soft one. Two types of ground are successively considered with bulk modulus $K = 9,260$ kPa and $K = 4,630$ kPa. The analysis is carried out for a gallery with 3.80 m inner diameter and 25 cm thickness. This under construction is part of the irrigation system of the “Los Ríos” county (Ecuador). Comprehensive computations in various hypotheses pointed out the significant effects of the interaction. The sectional stresses (M, N) in the gallery lining embedded in soft ground depend mainly of the gallery depth versus ground surface. Contrary, the mechanical characteristics of the surrounding ground resulted to have little influence.

Key words: Circular gallery (tunnel), interaction, structural analysis, finite element method (FEM).

1. Introduction

A large irrigation system (Proyecto PACALORI) is under construction in “Los Ríos” Province in Ecuador (Fig. 1). The system consists of two water intakes on the rivers Calabí and Vines-Quevedo capturing about $20 + 30.6 = 50.6$ m³/s water which is transported by a network of galleries reachig to a total length of 53 km in 13 artificial lakes created by 13 earth dams. The total volume of reservoirs reaches 798.4 hm³ ensuring irrigation during the dry season (June-December) of a potential surface of 103,876 ha [1].

This paper is referring to interection effects between a circular gallery (tunnel) and surrounding soft ground. The study is performed in the case of the gallery for water transport from Calabí river to Lechugal II reservoir (Fig. 1). The gallery is of 3.80 m inner diameter, has 0.25 m lining thickness, 3.5 km length and it will be built by TBM (Tunnel Boring Machine) technology. It conveys in free flowing 20 m³/s water to Lechugal II reservoir during dry season.

Geology, at regional level including the area of the gallery is made up mostly unconsolidated sediments that age corresponding to recent Quaternary deposits, and topped by volcanic ash. The geotechnical characteristics of surface materials show significant variations regarding the mechanical behavior. The geomorphological phenomena are generated by erosion and not necessarily by tectonic factors. The gallery area is considered a tectonically stable zone, free of fails and few seismic events with significant magnitude. The gallery alignment crosses a land of soft ground of different types: loose sand, rusty mud, sandy mud, sandy clay, gravels, sandstone, marl and other.

The gallery—surrounding ground interection effects are analysed in two cross sections of the gallery taking into account the linear elastic behavior for materials. The cross profiles P6 and P9 (Fig. 2) were selected from gallery route, they corresponding to minimum (14 m) and maximum (30 m) ground coverage over the key of the gallery sections. The stress/strain state in gallery linning and surrounding ground are evaluated in 2D and 3D for different mechanical characteristics of the ground running two software, respectively Geo Studio

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Fig. 1 Scheme of the PACALORI irrigation system from Los Rios Province (Ecuador).

Fig. 2 Upstream route longitudinal profile through the axis of the Calabí river intake—Lechugal II reservoir gallery.

Sigma W [2] and ABAQUS [3].

2. Calculation Procedures

The analyses are carried out in linear elastic

hypothesis for materials behavior. The gallery—surrounding ground unitary system was discretized in finite elements in both 2D (bi-dimensional) and 3D (three-dimensional) problems.

Fig. 3 illustrates two examples of 2D and 3D meshing applied in the analyses with ABAQUS.

The material characteristics used for structural analysis of the Calabí river—Lechugal II reservoir gallery were chosen based on in-site SPT (Standard Proctor Test) and literature data, they being presented in Table 1.

In order to evaluate the effects of the interaction between gallery lining and surrounding ground two groups of values for elasticity module and Poisson coefficient, respectively $E = 10,000$ kPa, $\mu = 0.32$ and $E = 5,000$ kPa, $\mu = 0.32$ were considered for ground.

The lithostatic pressures corresponding to the gallery key level were applied as constant pressure at the ground surface, these meaning 540 kPa for P9 profile and 252 kPa for P6 profile.

In ABAQUS the finite element types for 2D mesh were quadrilaterals with 4 nodes including incompatible mode (CPS4I) for ground modeling, respectively

beams (B21) for gallery lining modeling. The same types of elements were used in 2D analyses with Sigma W.

In 3D mesh with ABACUS BRICK8 elements with incompatible mode included were used for ground modeling, respectively SHELL elements for gallery lining modeling.

The type and number of elements used for meshing gallery lining-surrounding ground unitary system in various hypotheses of analysis are shown in Table 2. It may point out that elements used for gallery lining modeling (Quadrilateral, Beam, Brick, Shell) are linear ones and thus the circular shape of the gallery is approximated by a polygonal one. In these conditions it is important to use an important number of elements meshing the gallery lining perimeter.

Boundary conditions were applied to lateral and bottom edges of meshes. They consisted in blockage of the node translations on normal direction to edge surfaces and of all possible rotations.

Fig. 3 Finite element meshes by ABAQUS of the gallery-surrounding ground system in 2D and 3D problems.

Table 1 Material characteristics used for structural analysis.

Type of material	γ kN/m ³	E kPa	μ	K kPa
Concrete in gallery lining	24	24,000,000	0.2	13,000,000
Sandy clay	18	6,000	0.35	6,670
Mud	18	6,000	0.35	6,670
Gravel	18	18,000	0.30	15,000
Marl	21	40,000	0.25	26,670
Sandstone	21	40,000	0.25	26,670

Table 2 Type and number of finite elements.

Software problem type	Key gallery deepness	Type and number of finite elements					
		Ground			Gallery		
		Quadrilateral	Brick	Quadrilateral	Beam	Brick	Shell
P9 Abaqus 3 D $E_g = 10,000$ kPa	30		12,520	-	-	-	240
P9 Abaqus 3 D $E_g = 10,000$ kPa	30	-	12,520	-	-	240	-
P6 Abaqus 2 D $E_g = 10,000$ kPa	14	598	-	-	12	-	-
P6 Abaqus 2 D $E_g = 5,000$ kPa	14	598	-	-	12	-	-
P9 Abaqus 2 D $E_g = 10,000$ kPa	30	896	-	-	12	-	-
P9 Abaqus 2 D $E_g = 5,000$ kPa	30	896	-	-	12	-	-
Sigma W 2D Plane $E_g = 10,000$ kPa	14	13,601	-	1,350	-	-	-
Sigma W 2D Beam $E_g = 10,000$ kPa	14	13,601	-	-	270	-	-
Sigma W 2D Plane $E_g = 5,000$ kPa	14	13,601	-	1,350	-	-	-
Sigma W 2D Beam $E_g = 5,000$ kPa	14	13,601	-	-	270	-	-
Sigma W 2D Plane $E_g = 10,000$ kPa	30	14,774	-	1,350	-	-	-
Sigma W 2D Beam $E_g = 10,000$ kPa	30	14,774	-	-	270	-	-
Sigma W 2D Plane $E_g = 5,000$ kPa	30	14,774	-	1,350	-	-	-
Sigma W 2D Beam $E_g = 5,000$ kPa	30	14,774	-	-	270	-	-

Fig. 4 Contour lines of σ_v (S22) and σ_h (S11) stresses in ground around gallery lining (ABAQUS, 2D, $K = 9260$ kPa, Beam modeling gallery lining).

3. Results in Analyses

Some significant results obtained in the analyses carried out are presented in the followings 4 to 10 figures.

Fig. 4 points out that gallery lining being much more stiffer than the surrounding ground attract loads from

outside sector of the vertical planes tangent to gallery abutments. The loads attracted are directly proportional to the ratio $E_{c, \text{gallery lining}}/E_{g, \text{ground}}$.

Fig. 5 confirms that τ_{xy} (S12) (shear stresses) in vertical planes tangent to gallery abutments are downward on the face of the sector over gallery. They are diminishing in elevation and reach 0 at about 6 m

over key gallery level for 30 m gallery depth versus ground surface.

The contour lines of vertical stresses $\bar{\sigma}_v$ (S_{22}) in ground computed in 3D analysis (Fig. 6) have similar shapes with those resulted from 2D analysis.

The vertical stresses $\bar{\sigma}_v$ (S_{22}) and horizontal stresses $\bar{\sigma}_h$ (S_{11}) in gallery lining meshed with Brick elements processed as sectional stresses (M, N) led to similar diagrams with the case of gallery lining meshed with Shell elements. However, last case leads to a more flexible structure with significant effect on bending moment value M at gallery abutments (see Table 3).

Fig. 5 Contour lines of τ_{xy} (S_{12}) stresses in ground around gallery lining (ABAQUS, 2D, $K = 9,260$ kPa, Beam modeling gallery lining).

Fig. 6 Contour lines of $\bar{\sigma}_v$ (S_{22}) stresses in ground surrounding gallery lining (ABAQUS, 3D, $K = 9,260$ kPa, Shell modeling gallery lining).

Fig. 8 illustrates contour lines of the horizontal stresses $\bar{\sigma}_h$ (S_{33}) on longitudinal direction of the gallery. The stresses are 4-5 times less than $\bar{\sigma}_v$ (S_{22}) $\bar{\sigma}_h$ (S_{11}) in the cross section of the gallery.

Fig. 9 presents diagrams of the vertical stresses $\bar{\sigma}_v$ (S_{22}) in a horizontal section, tangent to gallery key. It may remark the increase of stresses above gallery cross section because of its higher relative stiffness versus surrounding ground.

As is expected the reduction of the ratio $E_{c, \text{gallery lining}}/E_{g, \text{ground}}$ led to some reduction of the bending moments at the gallery key. Contrary the variation of the axial forces is insignificant one (Fig. 10).

Fig. 7 Contour lines of σ_v (S22) and σ_h (S11) stresses in gallery lining (ABAQUS, 3D, $K = 9,260$ kPa, Brick8 modeling gallery lining).

Table 3 Values of sectional stresses in the gallery lining.

Calculus method Software problem type	Element type		M [kNm]			N [kN]		
	Ground	Gallery	Key	Abutment	Apron axis	Key	Abutment	Apron axis
Historical stresses method without interaction P9, H = 30 m	-	-	451	406	405	328	1,093	794
Abaqus 3D P9, H = 30 m Eg = 10,000 kPa	Brick	Shell	197	477	197	702	1,590	702
Abaqus 3D P9, H = 30 m Eg = 10,000 kPa	Brick	Brick	204	212	204	549	1,660	549
Abaqus 2D P6, H = 14 m Eg = 10,000 kPa	Quadrilateral	Beam	183	184	183	291	770	291
Abaqus 2D P6, H = 14 m Eg = 5,000 kPa	Quadrilateral	Beam	202	203	202	287	776	287
Abaqus 2D P9, H = 30 m Eg = 10,000 kPa	Quadrilateral	Beam	442	442	442	610	1,683	610
Abaqus 2D P9, H = 30 m Eg = 5,000 kPa	Quadrilateral	Beam	474	474	474	611	1,670	611
Sigma W 2D P6, H = 14 m Eg = 10,000 kPa	Quadrilateral	Plane	92	102	90.4	306	688.4	280.4
Sigma W 2D P6, H = 14 m Eg = 10,000 kPa	Quadrilateral	Beam	134.5	137.5	135.7	273.6	600.8	324.8
Sigma W 2D P6, H = 14 m Eg = 5,000 kPa	Quadrilateral	Plane	92	111.4	99.7	306	703.9	266.5
Sigma W 2D P6, H = 14 m Eg = 5,000 kPa	Quadrilateral	Beam	141.5	145.2	151.8	307.4	704	320.9
Sigma W 2D P9, H = 30 m Eg = 10,000 kPa	Quadrilateral	Plane	192.2	198.4	181.2	700.4	1,363.9	636.6
Sigma W 2D P9, H = 30 m Eg = 10,000 kPa	Quadrilateral	Beam	272.4	278.3	275.7	575	1,209.4	625.8
Sigma W 2D P9, H = 30 m Eg = 5,000 kPa	Quadrilateral	Plane	213.3	219.2	200.5	707.1	1,385	607.5
Sigma W 2D P9, H = 30 m Eg = 5,000 kPa	Quadrilateral	Beam	308	311.2	304	566	1,219	617.6

Fig. 8 Contour lines of σ_h (S33) stresses in gallery lining on longitudinal direction (ABAQUS, 3D, $K = 9,260$ kPa, Brick8 modeling gallery lining).

Fig. 9 Vertical σ_v (S22) diagram stresses in ground on horizontal section at gallery key level for various E_{ground} (ABAQUS, 2D, Beam modeling gallery lining).

Fig. 10 Sectional stresses (M, N) diagrams in gallery lining for various E_{ground} (ABAQUS, 2D, Beam modeling gallery lining).

In Table 3, it is centralized presented the values of sectional stresses (M, N) in the gallery lining for all

mesh variants considered in this study. For initial, it may remark from Table 2 that meshes run in ABAQUS

were coarse ones, while the meshes run in Sigma W were refined ones. A coarse mesh led to a higher stiffness of the gallery structure with important effects on M values. Refined meshes run in Sigma W led up to 50% reduction of the equivalent M computed by coarse mesh run with ABAQUS.

All variants run emphasized that sectional stresses (M , N) and of course and other output parameters (strains, displacements, unitary stresses) have a linear variation function of the gallery depth versus ground surface.

The discretization with Beam elements of the gallery lining led always to higher values M versus their equivalents computed using Quadrilateral (Plane) meshing gallery lining. The differences reach to 40% for bending moments M and to 15% for axial forces N .

3D coarse meshes run in ABAQUS allowed three-dimensional degrees of freedom for node displacements and the resulting values for M , N have become closer to their equivalents computed in refined 2D meshes run in Sigma W.

4. Concluding Remarks

The following concluding remarks can be formulated based on the result of the study:

- The stress states (M , N) in the galleries (tunnels) lining embedded in soft ground mainly depend of the underground structure deepness versus ground surface. The sectional stresses (M , N) have a linear variation function of the gallery depth versus ground surface. The mechanical characteristics of the ground layers surrounding the gallery have generally insignificant influence. For instance a variation of 100% of the ground characteristics (5,000 kPa and 10,000 kPa) generated a variation of only 9% of the bending moments (M) in the gallery lining. Moreover the axial forces have varied even less, respectively 1.5%. This

result is different from the gallery built in hard ground (rocks) where above the gallery are born discharge vaults that depend of the mechanical characteristics of rocks and not of the gallery depth versus ground surface [4].

- Generally, the influence of the interaction between gallery structure and surrounding ground is an important one. The equivalent sectional stresses (M , N) in gallery lining without interaction are higher. Taking into account this interaction, the bending moments (M) in gallery lining in cases of refined meshes are reduced with about 50% versus their equivalent in neglecting interaction case.

- The bending moments in the gallery lining are sensitive with finesse (refinement) of the finite element mesh, element types, boundary conditions. Contrary, the axial forces are less sensitive. A coarse mesh led to a stiffer structure.

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