

Geotechnical Considerations in Well Casing Design

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Summary Offshore well casing must be designed to be not only structurally, but also geotechnically stable in accordance with API or other similar standards. Understanding the interaction of well components with the surrounding sediments is imperative, as it is these sediments that provide the resistance to applied vertical, lateral and torsional loading during both installation and operation of the well. At each stage of construction, from the placing of the temporary guide base to the completion of the well, the surrounding sediments need to resist the loads applied by the self weight of each well component and possible live loadings caused by snagging of any exposed well components or flow lines. The stages of component installation and, most importantly, the geotechnical properties of the surrounding sediments must be fully understood before any loading can be considered.

It has been found that the well and flow line layout also has a significant effect on the governing load combination and careful consideration must be given to possible snag load locations. This paper will outline the different types of geotechnical analyses that must be undertaken for the verification of offshore wells.

1 INTRODUCTION

Offshore well casing is usually completely designed before it is checked for geotechnical stability. Significant changes in the design after this stage would be expensive, so geotechnical stability issues are usually overcome by extending the existing structure (ie. increasing the initial grouted casing length or adding more high torque connectors).

The following geotechnical verifications should be conducted before the well casing design is finalised, and are outlined in this paper.

- Temporary guide base (TGB) stability
- Open hole stability
- Lateral capacity
- Bending induced cracking
- Axial capacity
- Torsional capacity
- Effects of drilling mud

These types of analyses are also relevant for drilled and grouted piles, which are often constructed using well casing in offshore scenarios.

2 WELL CASING INSTALLATION SEQUENCE

Well casing installation consists of several key stages. At each stage, the well components must be supported by the surrounding sediments through the mudmat (or TGB) or the grouted casing (ie. no support is provided by the installation

vessel after each component is installed).

A typical well casing installation sequence is outlined (typical casing and drill hole dimensions have been used):

1. Place temporary guide base (TGB).
2. Drill 36" Internal Diameter (ID) hole to a depth of 48 m.
3. Insert 48 m long 30" Outer Diameter (OD) casing and suspend it from TGB.
4. Grout 30" OD casing in the 36" ID hole.
5. Drill a 17½" ID hole through the 30" OD casing to 470 m below mudline.
6. Insert 468 m long 13³/₈" OD casing.
7. Grout 13³/₈" OD casing in 17½" ID hole.
8. Mount blow-out preventer (BOP).
9. Drill a 12¼" ID hole through the 13³/₈" OD casing to an approximate depth below mudline of 2500 m.
10. Insert 2500 m long 9⁵/₈" OD casing.
11. Grout 9⁵/₈" OD casing in 12¼" ID hole.
12. Drill a 8½" ID hole through the 9⁵/₈" OD casing to an approximate depth below mudline of 3400 m.
13. Insert approximately 900 m long 7" OD liner into reservoir.
14. Complete the wellhead.

The geotechnical design of well casing is principally concerned with stages 1 to 7 listed above. A typical installation sequence showing installation stages 1 to 7 is presented on Figure 1.

3 LOADING COMBINATIONS

The loads applied to the well casing change during

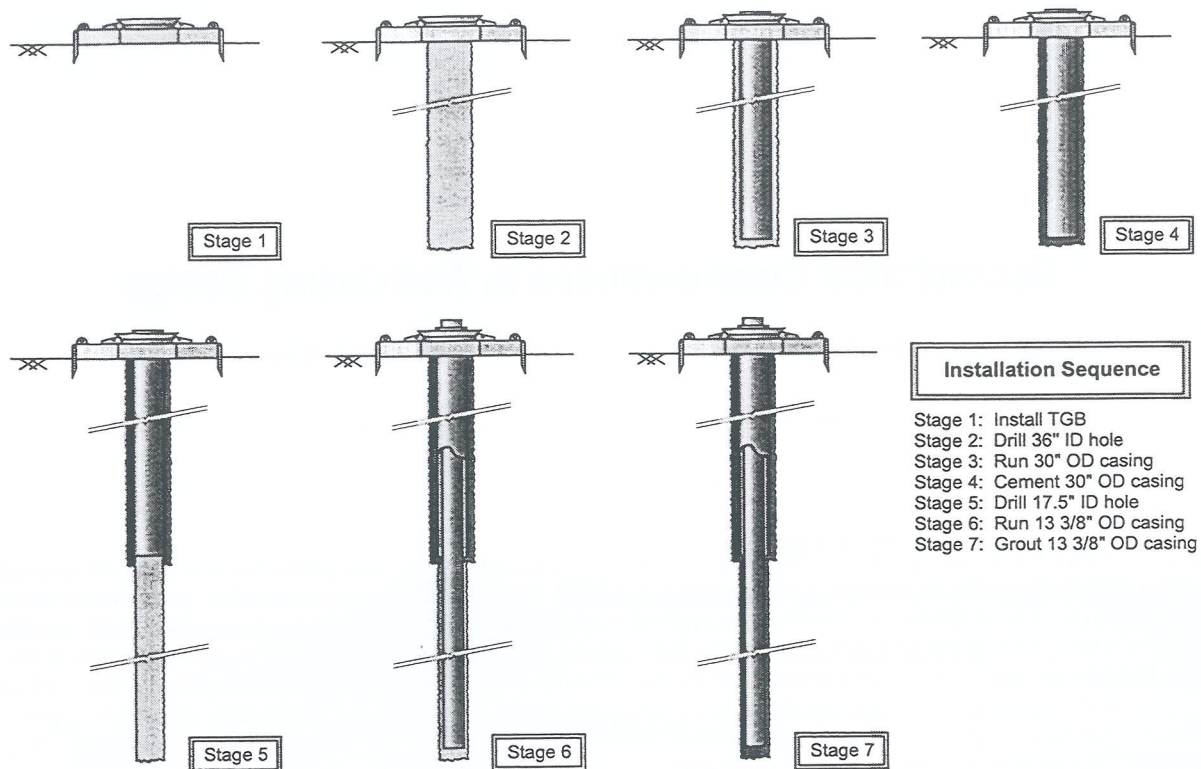


Figure 1: Well casing installation stages

installation and operation. At each stage of installation, the well must support the self weight of its components. Once installed, the well must support its self weight and any possible snag loading.

The loads acting on the well casing are assumed to be static, cyclic loading of the casing is not expected and thus only static loading is usually analysed.

3.1 Axial Loading

The axial loading on the well casing consists of the self weight of the well casing components. During installation this axial load changes, the most critical stages are:

- (i) when the hole is initially drilled through the TGB (Stage 2);
- (ii) when the TGB supports the ungrouted first casing (Stage 3);
- (iii) when the grouted first casing supports the ungrouted second casing (Stage 7); and
- (iv) when the grouted second casing supports the rest of the well casing string (Stage 10).

3.2 Snag Loading

Well casings must be designed to withstand an applied snag load, to cover the scenario of a boat anchor or trawling net catching on a well component and the load is often considered to be in the range of 100-200 kN. Snag loading is assumed to be applied as a temporary horizontal load acting at any point of the well-head structure and surrounding flow lines that can be snagged. Usually the worst lateral and torsional loading positions are checked.

3.2.1 Lateral loading

Snag loading of the well head or surrounding flow lines can induce a lateral load and/or a moment acting at the well casing head which must be resisted by the surrounding sediments.

3.2.2 Torsional Loading

Snag loading applied to the well head or surrounding flow lines can cause torsional loading on the well casing that must be resisted by the surrounding sediments. The ability of the flow lines to sustain a snag load needs to be considered. The amount of torsion that can be transferred from the flow line to the well casing depends on the ability of the flow line to transfer torsional loading without yielding.

4 TEMPORARY GUIDE BASE

In well construction, the first sections of casing are suspended from a temporary guide base (TGB). The TGB is usually in the form of a mudmat with a central hole through which the casing is installed. Only axial loads, in the form of the self weight of the TGB and first casing, act on the TGB during installation. Once the first casing is grouted, it supports all further applied loads.

The TGB settlement should be calculated for both touchdown and the stage where the first casing is hung from it (Stage 3). The stability of the TGB sitting over the open drill hole (Stage 2) should also be calculated.

4.1 Geotechnical Parameters for TGB Settlement and Stability

To calculate the TGB settlement and stability with any degree of accuracy, the strength profile of the soil over the top 5 m should be established. The following soil parameters are required for axial load and settlement analysis and TGB stability:

- Effective unit weight.
- Undrained shear strength (cohesive soils), or earth pressure coefficient at rest and interface friction angle (sands) (for calculation of stability at Stage 2).
- Small strain shear modulus.

4.2 Settlement at Touchdown

The touchdown settlement of the TGB is a function of the underlying sediments strength and deformability. The bearing capacity of the TGB must be checked and the associated settlements calculated.

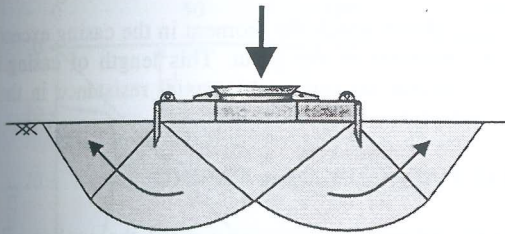


Figure 2: Bearing failure of TGB

4.3 Stability at Stage 2 - Unsupported hole collapse

Before the first segment of casing is installed, the TGB is sitting on an open hole. At this stage, an unsupported hole could collapse due to the weight of the TGB, illustrated in Figure 3. This is of particular importance in uncemented and cohesionless sediments or very soft cohesive sediments.

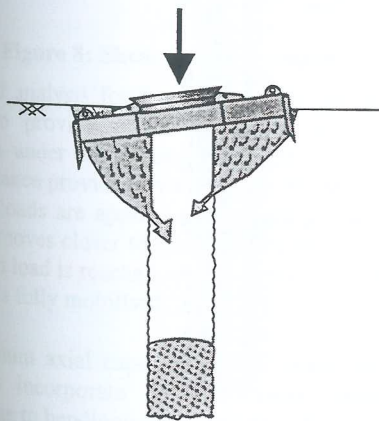


Figure 3: Unsupported hole collapse

When the hole is first drilled, the surrounding soil will respond in an undrained manner, pore water suctions are generated within the soil in response to changes in boundary conditions, such as drilling a hole or applying an external load. While these pore suctions remain, the soil may remain stable. With the passage of time, these may dissipate and hole

collapse may occur.

The risk of hole collapse can be minimised by ensuring the time between drilling the hole and installing and grouting the casing is kept to a minimum.

Drilling fluid smeared on the sides of the hole provides a seal between the water and sediment. This assists the sediment by forming suction pressures that remain stable by reducing the pressure differential between the soil and the water in the open hole. The extent of the support, provided by the drilling fluid, is not considered to be reliable under the conditions present in the near surface sediments.

4.4 Stability at Stage 3 - UngROUTED First Casing

After the first casing is installed (before grouting), the TGB must support the casing self weight, and at this stage further settlement of the TGB is anticipated. The empty annulus between the casing and the hole is also susceptible to hole collapse, with the sediments collapsing into the annulus. This type of collapse is not serious as the grout pressures are usually high enough to push the collapsed sediments back into place, but it could lead to larger settlement of the TGB.

5 LATERAL CAPACITY OF A CASING

The capacity of the casing to resist lateral loads is dependent on the lateral resistance provided by the near surface sediments, shown schematically in Figure 4. The casing resistance to the lateral loading typically affects only the top 20 diameters of casing, whereas the first casing string is usually over 45 diameters long. This depends on the load size and the lateral resistance provided by the sediment.

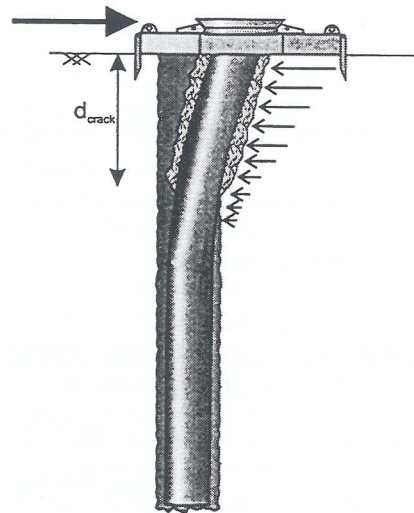


Figure 4: Lateral load on casing

5.1 Geotechnical Parameters for Lateral Analysis

The accuracy of the analysis depends on the definition of the ultimate lateral soil resistance, p_{ult} , and the shape of the p - y curves. The following soil parameters are required for lateral analysis:

- Effective unit weight.
- Undrained shear strength (cohesive soils), or earth pressure coefficient at rest and interface friction angle (sands).
- Shear modulus.
- The strain corresponding to one half the maximum principal stress difference in a laboratory compression test.

5.2 Lateral Analysis

The ability of the well casing assembly to resist a horizontal snag load can be analysed using a computer program such as LPILE¹. This program allows for differential rotation and lateral displacement of the grouted casing along its length, and includes appropriate modelling of the sediment behaviour using lateral load/displacement (p-y) curves.

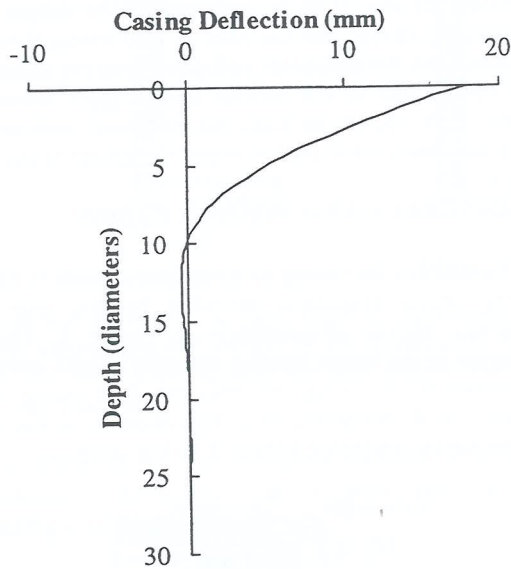


Figure 5: Casing deflection under lateral loading

A typical casing-head deflection curve for well casing in a low strength cohesive sediment is shown in Figure 5.

5.3 Grout cracking due to bending

Lateral loading can cause the grout between the casing and the soil to crack due to tensile bending stresses. This can adversely affect the shear transfer capacity of the casing (axially and torsionally) over this section, resulting in a reduced overall capacity of the casing. The cracking of the grout is accounted for in axial and torsional analyses by assuming the length over which the grout is cracked has zero shear transfer capacity in axial and torsional analysis.

The depth to which grout cracking may occur due to bending, caused by lateral loading of the casing, can be calculated by determining the curvature at which the tensile cracking strain exceeds the tensile cracking strain of the grout.

Figure 6 shows the distribution of moment down the casing under an applied snag load and the maximum cracking moment of the grout. The grout is assumed to be cracked over

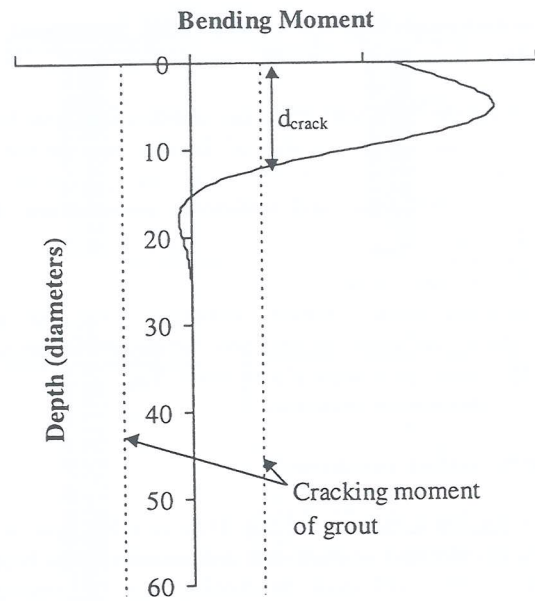


Figure 6: Distribution of moments down casing

a length d_{crack} , above which the moment in the casing exceeds the cracking moment of the grout. This length of casing is assumed to provide no torsional or axial resistance in their respective analyses.

6 AXIAL CAPACITY OF A CASING

The casing/grout-soil interface must resist the applied axial load by transferring the load from the casing to the soil, shown schematically in Figure 7.

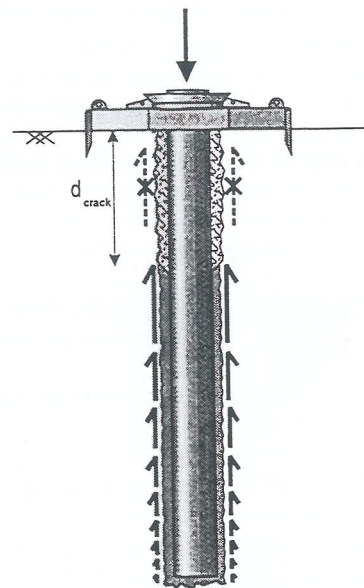


Figure 7: Axial loading on casing

6.1 Geotechnical Parameters for Axial Analysis

The geotechnical parameters required for axial analysis are:

- Undrained shear strength (cohesive soils), or coefficient earth pressure at rest and interface friction angle (sands).
- Peak shaft friction.
- Small strain shear modulus.

- Residual shear stress.
- Displacement to residual shear stress.

These parameters define the axial response of the soil-casing interface.

6.2 Axial Analysis

The axial resistance to each axial loading stage can be estimated using a non-linear, axial load transfer program such as RATZ². This program treats the casing as an elastic bar, with properties that may vary along the length. Interaction with the soil is characterised by discrete, non-linear springs that are distributed at regular intervals along the embedded section of the casing. The t-z curve is a function that relates the local shaft friction at the casing-soil interface to the current casing displacement, taking account of the previous displacement history. The shape of this curve strongly depends on the geotechnical parameters input into the analysis.

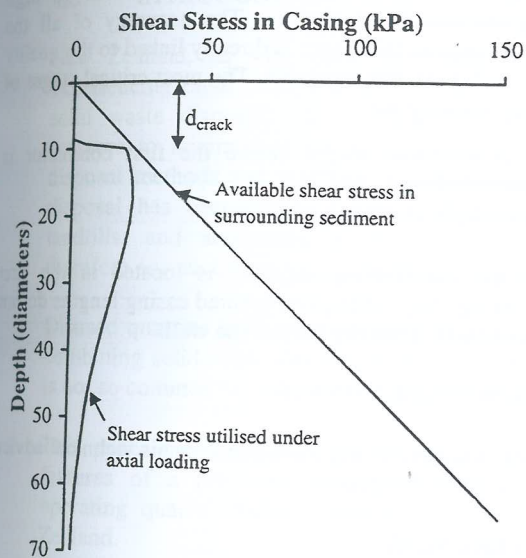


Figure 8: Shear Stress in casing

In the axial analysis for the well casing, the length d_{crack} , is assumed to provide no axial resistance. A shear stress distribution under an applied axial load, and the available shear resistance provided by the soil, is presented in Figure 8. As higher loads are applied to the casing, the utilised shear stress line moves closer to the available shear stress line until a maximum load is reached where the available shear strength of the soil is fully mobilised.

The maximum axial capacity of the casing should be high enough to incorporate the detrimental effects of grout cracking due to bending/torsion (Section 5.3) and the possible reduction of axial capacity due to the type of drilling mud used (Section 9).

6.3 Casing-Grout Shear Transfer

Shear transfer keys or weld beads may be required to transfer the axial load from the steel casing to the surrounding grout. Shear transfer keys are required in the regions of the casing

where the shear stress distribution induced by the applied axial load exceeds the shear transfer capacity of the steel-grout bond.

7 TORSIONAL CAPACITY OF A CASING

The torsional response of the casing is analysed by considering the remaining shaft friction available for mobilisation after allowance is made for the shaft friction, which has already been mobilised under axial loading, shown schematically in Figure 9.

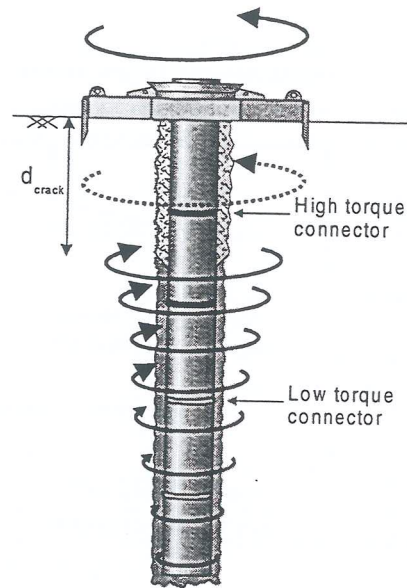


Figure 9: Torsional load on casing

The connectors used to join the lengths of casing can be normal "low torque" connectors (not capable of transferring significant torque) or "high torque" connectors (that are capable of transferring torque to the next length of casing). These high torque connectors are relatively expensive and it is preferential to use the minimum number of connectors possible in well design.

7.1 Geotechnical Parameters for Torsional Analysis

The following soil parameters are required for the torsional analysis:

- Undrained shear strength (cohesive soils), or coefficient earth pressure at rest and interface friction angle (sands).
- Shear modulus.

7.2 Torsional Analysis

Torsion applied to the casing at the seabed is transmitted down the casing, gradually decreasing with depth, as the torsion is dissipated into the soil by circumferential shear stresses resisting the casing motion. Any torsional transfer capacity of the grout, surrounding the casing, is considered to be minimal and is ignored in the torsional analysis.

The torsional resistance of the casing-soil interface can be analysed using a non-linear torsional load transfer computer program. The axial load transfer computer program RATZ²

can also be used to analyse torsionally loaded piles by using an equivalent set of torsional parameters in place of the standard axial parameters (this approach has been validated by the author of RATZ²).

Figure 10 shows the distribution of torque down a typical casing in weak, cohesive sediment. The torsional transfer capacity of a normal "low-torque" connector is shown, and in this case, high torque connectors between casing segments are required to a depth of about 20 diameters. Casing segments are typically 9-12 m long, and under the applied load, the casing would require 1-2 high torque connectors.

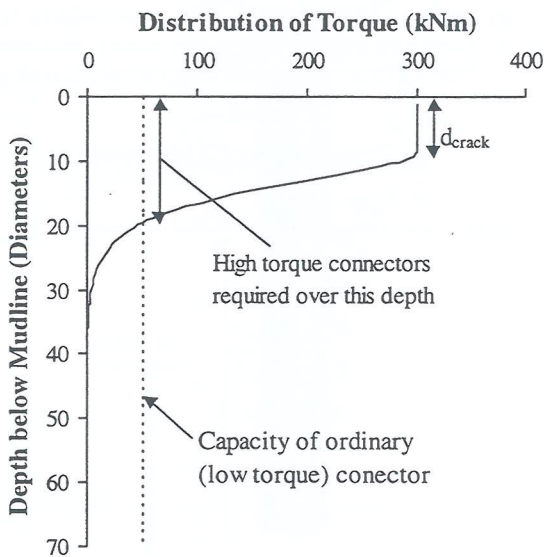


Figure 10: Distribution of torsion down pile

8 THERMAL LOADING ON CASING DUE TO GROUT SETTING

As the grout around the casing sets, the temperature in the grout and the casing will rise. During this time, the steel casing will expand. As the grout cools to the ambient temperature, the casing will contract again. This expansion and contraction of the steel casing is known as thermal straining. These thermal strains can lock in residual stresses at the casing-soil interface, which should be incorporated into casing capacity analyses.

Thermal strain can be incorporated into the axial analysis as a loading cycle that is applied before the static axial load (ie. the dead weight of the next casing). Typical temperature changes of approximately 35°C can be expected in the casing due to grout setting.

9 EFFECTS OF DRILLING MUD

The type of drilling fluid (drilling mud) used in the creation of the hole for the casing can affect the shaft friction on the grout/soil interface. Drilling mud smears along the sides of the hole wall during the course of drilling, and even flushing the hole with water cannot guarantee removal of all mud.

Eide and Aas³ suggest bentonite drilling mud can reduce the

effective shaft friction between a grout and sediment by up to 25%. This can be accounted for conservatively by decreasing the peak axial capacity of the casing by 25% if bentonite drilling mud is used in the well construction.

10 GROUT COVERAGE

The consistency of the grout is relatively liquid to assist with workability. Excess grout is pumped into the annulus between the soil and casing until grout return is observed at the top of the casing. The effect of hole collapse around the casing may inhibit some grout coverage over the top section of the casing. This section is usually assumed to have no load transfer capacity due to cracking under lateral loading, and therefore the extent of grout coverage over this section is not considered critical.

11 CONCLUSION

Optimisation of well casing design is dependent on high quality geotechnical information. The accuracy of all the analyses outlined in this paper is directly linked to the quality of the geotechnical data available. The most critical stages of well casing stability are:

- The construction stages before the first conductor is grouted; and
- The application of snag loading.

Most of the load-bearing capacity is located in the first grouted casing. Any subsequent grouted casing lengths do not significantly add to the capacity of the well.

12 ACKNOWLEDGMENTS

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13 REFERENCES

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