INTERNATIONAL SYMPOSIUM ON
DAMs IN A GLOBAL ENVIRONMENTAL CHALLENGES
Bali, Indonesia, June 1ST – 6TH , 2014

COULD THE FAILURE OF TETON DAM HAVE BEEN PREVENTED WITH AN EFFICIENT MONITORING PLAN?

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ABSTRACT:
After the failure of Teton Dam, which had a maximum height of 92 m, through a process of piping within the material from the earthfill, scientists determined that the dam had no type of monitoring instruments. The following question emerged from this finding: Could the failure of Teton Dam have been prevented if the dam had been adequately monitored? In this paper, the author employs 40 years of experience in the areas of monitoring and dam safety to analyze this question. The author concludes that if Teton Dam had been adequately monitored, an early warning about the piping process could be established and may have prevented this failure or avoided fatalities and significant damage downstream.

1. INTRODUCTION

The failure of Teton Dam, which occurred in Idaho in the United States (US) on June 1976 during the first filling of the reservoir, resulted in 14 deaths and material damages estimated between 400 million and 1 billion dollars (US$). With a maximum height of 92 m relative to the original valley, the failure of the dam was caused by a process of piping through the cut-off trench in the right abutment, which developed rapidly without the possibility of stopping the filling or releasing materials that may have stopped the erosion process [1].

Despite the large height of the dam and the use of wind-deposited silt (which is highly susceptible to piping) as compacted earthfill in the construction of the dam, no instrumentation was employed, with the exception of a few surface displacement landmarks. The foundation of the dam was not monitored [2].

The aim of this study is to analyze the benefits of an adequate dam monitoring plan, which could have been used to provide early warnings about piping problems, to prevent the failure of the dam or to significantly reduce damage downstream.

2. SUMMARY OF THE DEVELOPMENT OF THE ACCIDENT

The failure occurred on June 5, 1976. On June 3, 1976, springs with an outlet of clean water were observed approximately 400 to 450 m downstream of the dam. No upwelling or other signs of increasing infiltration were observed downstream of the dam prior to June 3. These infiltrations occurred through the joints in the rock of the right abutment with an estimated flow rate of 400 l/min.

On June 4, 1976, a small springs with an estimated flow rate of 80 l/min was observed in the same abutment approximately 60 m downstream from the foot of the dam. Prior to this date, no major concerns with these springs were identified because the water was clear and filling of the reservoir was underway.

On June 5, 1976, a muddy flow with an estimated flow rate between 600 and 800 l/s was observed on the talus of the right abutment (approx. el. 5,045 m) after 7:00 AM; a small brook of muddy was also observed on the right abutment at an el. of 1,537 m. These infiltrations occurred at the junction of the earthfill and the abutment; both increased considerably during the three subsequent hours. At approximately 10:30 AM, a large infiltration (approx. 450 l/s) appeared on the face of the earthfill. This infiltration, which progressively increased, appeared to emerge from a “tunnel” that was approximately 2.0 m in diameter and perpendicular to the dam axis. This tunnel was transformed into an erosion well, which developed a slope overhead and curved in the direction of the right abutment.

At 11:00 AM, a vortex appeared in the reservoir at approximately station 14+00 near the crest. At 11:30 AM, a small sinkhole appeared in the erosion channel that developed in the downstream slope near the crest. At 11:55 AM, the dam crest began to break and subsequently produced the breach formation located between the vortex and the downstream erosion channel.

Five hours elapsed between the moment when the first responders to the dam location observed the first springs with turbid water and the dam collapse. Approximately 15 hours elapsed between the appearance of the first surface manifestations of piping and the dam collapse.

Data prior to the failure of Teton Dam are not available, with the exception of the increase in water level in various sounding holes located in the abutments; however, this information has minimal value.

3. OPINION OF THE CONSULTANTS REGARDING THE INSTRUMENTATION AND FIELD INSPECTIONS

The board of nine advisors that analyzed the causes of the Teton accident, which included Arthur Casagrande, Thomas Leps and Ralph Peck, reported that the measurements for a dam of this size and complexity should have included surface marks to measure the vertical and horizontal displacements, settlement gauges and inclinometers to measure the internal displacements of the earthfill and piezometers to measure the pore pressures in the interior of the earthfill and the foundation [1]. In addition to these instruments, the advisors recommended the installation of flow meters and wells to observe and measure the water level near the reservoir and instruments such as accelerometers to assess the performance of seismic records.

They noted that the inspectors responsible for visual observations should have been equipped with a manual of operation instructions to guide them in their routine inspections. These individuals should have been trained to interpret potential adverse conditions and to promptly report any anomalous conditions.

4. CONDITIONS THAT FAVOR PIPING THROUGH THE CUT-OFF TRENCH

The wind-deposited silt used in the earthfill and the cut-off trench of the right abutment were highly susceptible to piping. This finding was recognized by the United States Bureau of Reclamation (USBR) at the beginning of the project and confirmed by the Board of Consultants that investigated the causes of the accident. This material may be compromised and rapidly transported if subject to percolating water. Regressive erosion from downstream to upstream was not involved because this action requires a considerable amount of time.

Thus, the initial rupture of the earthfill of the cut-off trench can be attributed to erosion by direct contact of percolating water with the earthfill. This contact may have occurred due to two conditions: in the first condition, the earthfill was in contact with open joints in the rock at the base of the trench, through which the percolating water began the entrainment of the soil; in the second condition, the percolating water passed through the joints of the earthfill. The physical conditions near station 14+00 contributed to both possible scenarios, which may have developed simultaneously.

The erodibility of the earthfill material is also dependent on its density and the state of confining stresses. The erodibility of locations with soft material, such as in localized zones in which compaction was difficult or impractical, was substantially greater than locations with compacted earthfill. Erosion develops rapidly in locations with low intergranular pressures compared with locations with high intergranular pressures. Conversely, if the water pressure exceeds the intergranular pressure, tensile stress develops in the solid skeleton. When this stress exceeds the tensile strength of the soil, the soil can fissure via a process known as hydraulic fracturing.

These conditions occurred near the base of the cut-off trench around station 14+00 and were responsible for the failure of the earthfill of the cut-off trench. The existence of open joints in the foundation rock upstream of the cut-off trench may have transmitted high hydrostatic pressures that favored piping through one of the two previously mentioned mechanisms.

5. MONITORING PLAN FOR ÁGUA VERMELHA DAM

The hydroelectric facility of Água Vermelha, which has an installed capacity of 1,380 MW, is located in Brazil along the Grande River, on the border between the states of São Paulo and Minas Gerais and downstream from the Marimbondo Hydroelectric Power Plant (UHE Marimbondo). The plant includes a dam with a maximum height of 63 m and a length of 3,920 m with concrete structures located on the river bed and earthfill dams that complete the dam on both banks.

The filling of the reservoir was performed in 1978. During the earthfill dam project, particularly in the region of the left abutment, some measures were employed from lessons learned from the failure of Teton Dam, which occurred on June 5, 1976. An extensive report that substantiated the findings of the Board of Advisors, who analyzed the causes of the accident, was published in December 1976.

A highly permeable layer of agglomeratic lava (10^{-1} cm/s) was identified in the foundation of the left abutment of Água Vermelha Dam, which required detailed studies in the design phase. Due to the Teton accident in 1976, a concrete wall was constructed upstream of the cut-off trench, in the foundation of the left abutment, to ensure a good seal. A grout curtain was constructed with three lines of grout holes which penetrated the abutment as shown in Fig.1.

The instrumentation plan for the region of the left abutment of Água Vermelha Dam consisted of two cross-sections in the cut-off region with upstream and downstream piezometers and two additional abutment sections to control the water pressures in the region of the abutment. A flow meter was installed in the output of the drain of station 191+10 m, and water samples were collected from the reservoir and this drain, during the filling of the reservoir, to measure the concentration of solids in suspension and dissolution [3].

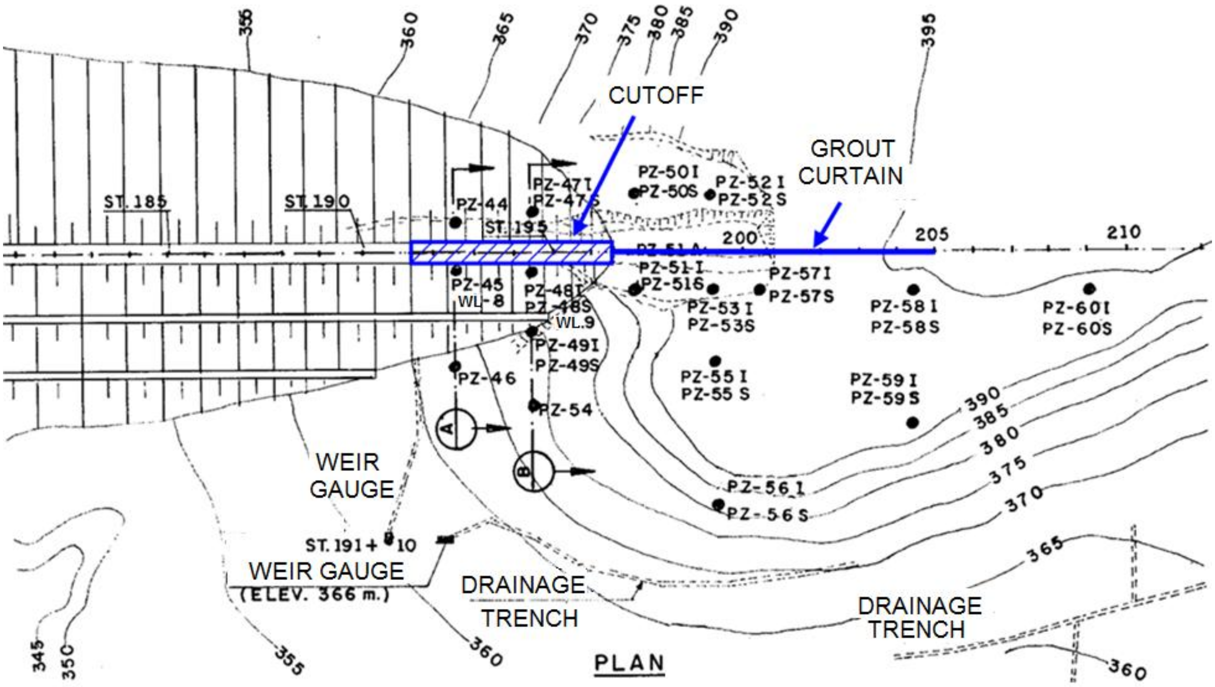

Figure 1 - Layout of the instrumentation at the left abutment in Água Vermelha earthfill dam.

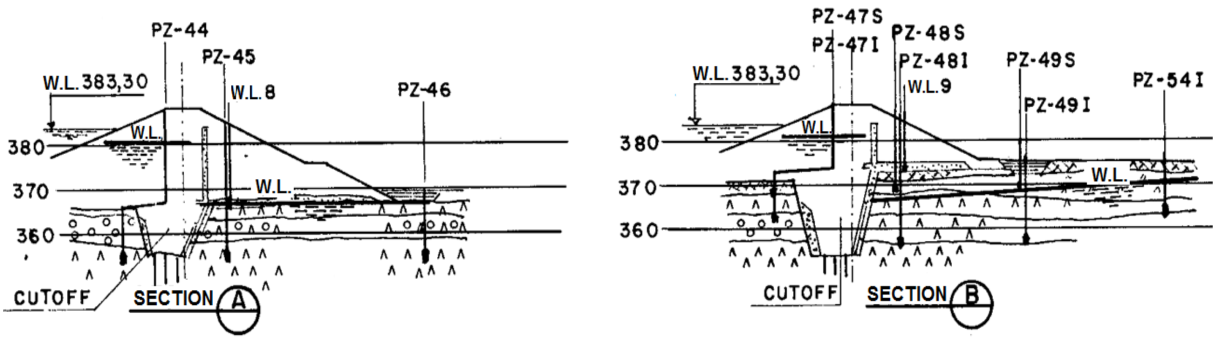

Figure 2 - Layout of instrumentation in the cutoff trench.

The positive results provided by the instrumentation in the region of the left abutment of Água Vermelha Dam permitted the three-dimensional analysis model of percolation conditions through the abutment. The results shown in reference [4] confirm the excellent performance of the cut-off trench with the upstream concrete wall.

The piezometers installed upstream and downstream of the cut-off at their average elevations permitted the calculation of the sealing efficiency of this device after filling. In March 1979, this efficiency achieved an 82%, as a probable contribution of the concrete wall upstream of the agglomeratic lava layer.

6. PROPOSED MONITORING PLAN FOR TETON DAM

Based on the experience acquired from the instrumentation of the left abutment of Água Vermelha Dam [4] and [5], the problems that caused the failure of Teton Dam could have been prevented if the dam had been equipped with adequate monitoring instrumentation.

The monitoring plan proposed for the right abutment of Teton Dam, in the region in which a deep cut off trench was executed, included the installation of piezometers, settlement gauges, inclinometers, surface displacement landmarks and flow meters, as proposed by the advisors who analyzed the causes of the accident. Based on their suggestions, a minor alteration was also proposed, which consisted of the substitution of inclinometers for the total pressure cells, installed next to the base of the cut-off. The inclinometers would indicate the relief of stresses resulting from the soil arching process between the soil of the cut-off and the foundation rock.

The general arrangement of the instrumentation proposed for the right abutment of Teton Dam is shown in Fig. 3; instruments should be installed in a minimum of 2 cross-sections of the deep cut-off. In this instrumentation arrangement, the installation of standpipe piezometers, upstream of the cut-off, is possible as shown in Fig. 3, providing that the tubing does not rise vertically and incorporates a subhorizontal section with the proper slope to prevent air bubbles. A similar scheme was employed in the left abutment of Água Vermelha Dam with satisfactory results.

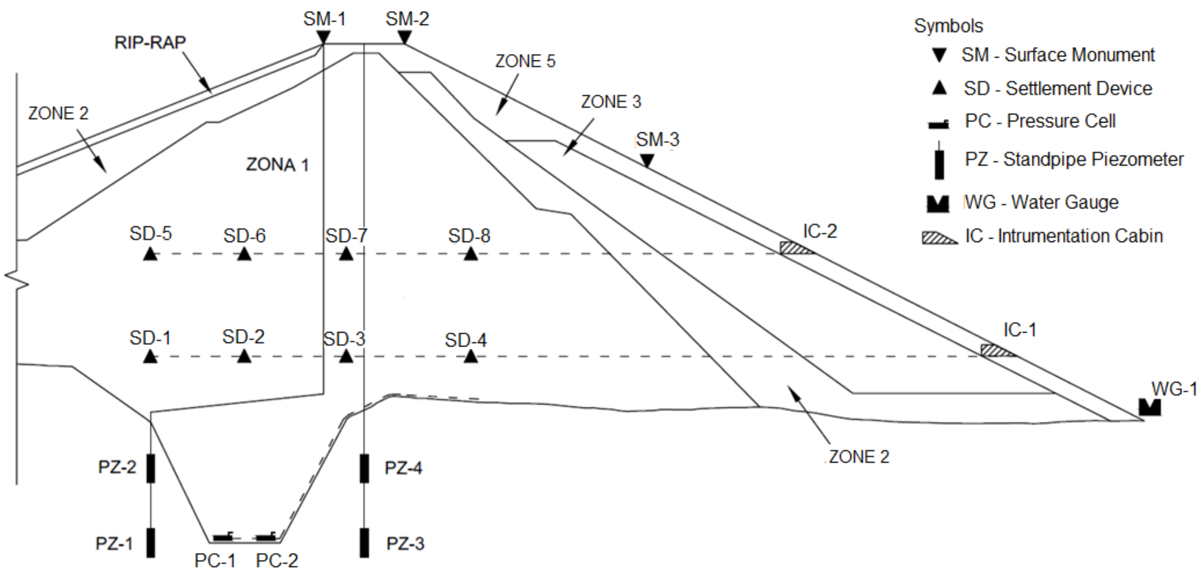

Figure 3 - Instrumentation layout proposed for the right cut-off trench of Teton Dam.

The following objectives are emphasized as primary justifications for this monitoring plan:

- Piezometers PZ-1 and PZ-3 are installed on the same level of the base of the cut-off. They should permit prompt detection of piping initiated on the earthfill-rock interface near the cut-off base.

- Piezometers PZ-2 and PZ-4 should be installed midway along the cut-off. They would permit the detection of piping through the earthfill of the cut-off caused by hydraulic fracturing on the interior of the cut-off, which is attributed to the soil arching process.

- The settlement cells CR-1 to CR-8 should be installed inside of the earthfill above the cut-off at two distinct elevations. They help to evaluate the effects of arching caused by the cut-off and enable better calibration of the mathematical analysis models.

- The surface marks function as supports in the evaluation of the settling of the dam and its foundation.

 - Flow meters should be installed next to the downstream foot of the dam, as recommended by the advisors.

The information transmitted by the instruments installed during the construction process, or prior to the construction process as in the case of the foundation piezometers, would inform about the piping process in the cut-off region, since the beginning. By positioning the piezometers at the same level upstream and downstream of the cut-off, prompt detection of the loss of efficiency is possible according to the following example.

At Agua Vermelha dam piezometers had been installed also at a very pervious layer between two basaltic lava flows, as shown in Fig. 4, they permitted the detection of the loss of efficiency of the cement grout curtain immediately after filling of the reservoir. For an unexplained reason, piezometer PZ-40, which is located upstream of this curtain, began to show an accentuated decrease in water pressures after March 1979 (Fig. 5), immediately after the reservoir achieved its maximum height. Simultaneously, PZ-41, which is located downstream, began to indicate a distinct increase in water pressures and a distinct loss of efficiency of the grout curtain on the dam axis.

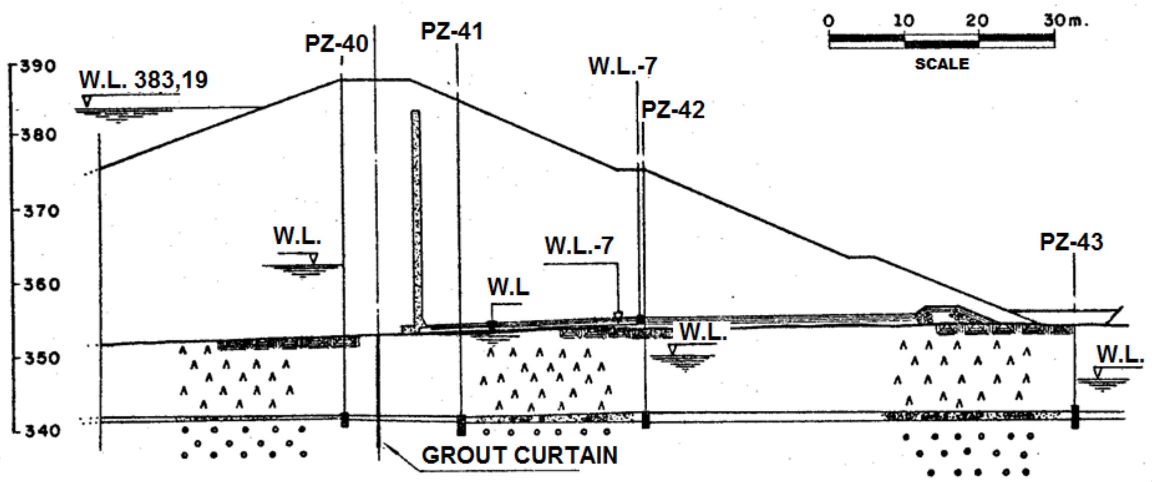

Figure 4 - Instrumentation layout at station 181+10 and piezometer water levels in Out/1979.

Similar to this example, the reduction in water pressures in the PZ-1 or PZ-3 piezometers for Teton Dam (Fig. 3), associated with the increase of the water pressures in PZ-2 or PZ-4, would have promptly indicated the beginning of a piping process, even during the filling phase of the reservoir. Due to the high susceptibility of the aeolian silts to the piping, the internal erosion process would have developed rapidly and been reflected in the rapid response of the foundation piezometers.

Associated with the measurement of the foundation piezometers, information transmitted by the settling cells, the total pressure cells and the flow meters, would help to detect and understand better the mechanism, which dangerously threatened the safety of Teton Dam.

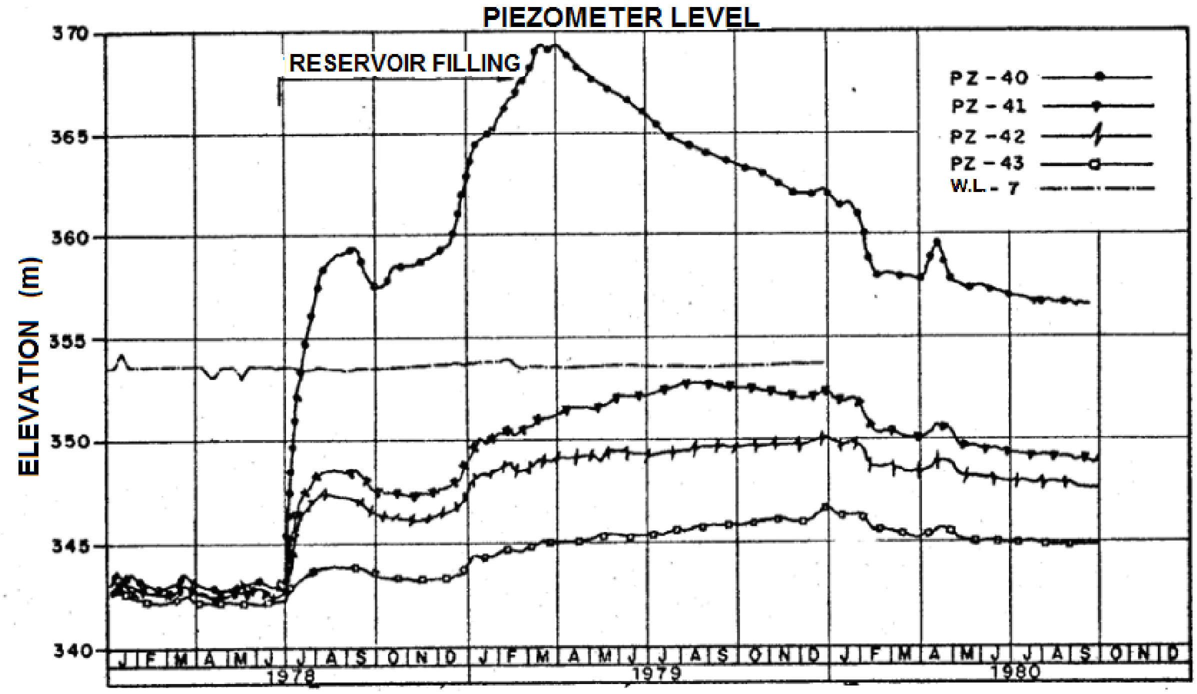

Figure 5 - Piezometer level changes at station 181+10.

The establishment of control values for the dam monitoring instruments during the design phase would be useful for the establishment of an early warning and the accurate detection of problems that threatened the dam safety.

7. PRIMARY CONCLUSIONS

The Board of Advisors that analyzed the causes of the failure of Teton Dam presented the following main conclusions:

- Wind-deposited clayey silts, which were used in the core and in the earthfill of the cut-off trench, were highly erodible. The use of this material adjacent to the intensely fractured rock of the abutment was a significant factor that contributed to the accident.

- The geometry of the cut-off trench with steep side slopes influenced the formation of cross-sectional arching, reduced the stresses around the base of the trench and favored the development of hydraulic fracturing, which may have created channels through the erodible material of the earthfill.

- The dam and its foundation were not adequately monitored with instruments to provide “Project Construction Engineering” and their team with the necessary information related to alterations in the earthfill and abutments during filling.

It is incomprehensible and lamentable that a dam of this size, with a maximum height of 92 m, was not properly monitored with the instruments included in its design and that the procedures and checklists from previous field inspections were not verified prior to the filling of the reservoir.

The instrumentation in the left abutment of Água Vermelha Dam may have provided an early detection of the events that led to the failure of Teton Dam. The general arrangement proposed in the cut-off region of the right abutment (Figure 3) for the monitoring of Teton

Dam was based on similar problems that occurred in Água Vermelha Dam. The findings conclude that it would have been possible to identify problems that developed in the foundation of Teton Dam, which eventually caused its failure.

Even if the proposed instrumentation had been installed, there most likely may not have been sufficient time to prevent the failure of Teton Dam, due to the rapid development of piping, or due to the excessive amount of time required for the analysis of instrumentation data and subsequent decision making. However, the early detection of the piping process by the instrumentation may have enabled adequate preparation of the design teams and field observers and the establishment of a warning and downstream evacuation plan, which may have prevented fatalities and significantly lessened the damage to downstream area.

8. KEYWORDS

Earth dam – Failure – Instrumentation – Dam safety

ACKNOWLEDGMENTS

The author is grateful to Eng. Sebastião Antonio Silva for his review of the study and his suggestions for technical improvement.

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