Structural message of the Tower of Babel

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Konstruktive Botschaft des Turms von Babel

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SUMMARY

The most famous Ziggurat, in its historical and structural identity, is chosen to exemplify the achievements in massive masonry construction of ancient Mesopotamia. The postulated disposition for its reconstruction is met, in the form of a pilot research study by generating few original technical parameters - in terms of mechanics and strength of materials. On this basis, some constructional essentials are specified.

RÉSUMÉ

Le plus fameux ziggurat, de par son identité historique et structurale, a été choisi comme exemple des structures massives en maçonnerie dans la Mésopotamie ancienne. Suivant certaines tendances visant à la reconstruction du monument, des recherches pilotes ont été faites, lequelles ont mené à la découverte de paramètres techniques originaux en ce qui concerne la mécanique et la résistance des matériaux. Sur cette base, certains problèmes majeurs de construction sont soulevés.

ZUSAMMENFASSUNG

Das durch seine historische und bauwerkliche Identität berümteste Zikkurat dient als Musterbeispiel vollendeter Massivbaukunst im alten Mesopotamien. Im Sinne einiger Tendenzen, die auf eine Rekonstruktion hinzielen, wurden Pilotuntersuchungen vorgenommen. Dabei wurden einige der urspünglichen technischen Parameter betreffend Mechanik und Werkstoffestigkeit entdeckt. Auf dieser Basis werden gewisse grundlegende Tragwerkseigenschaften dargelegt.

1. INTRODUCTION

In archaeology, it is the fate of all excavated ancient findings that, when not properly protected in good time against various effects of uncovering, they suffer accelerated destruction. This rule is fully confirmed in Babylon. Since the excavations of R. Koldewey, started in 1899 and carried on for ca. twenty years, the exposed remains were later, either widely touched by atmospheric influences (erosion and deflation) or human invasion (capture of bricks for present needs), resulting in major vanishing of the relics under sand and rubble.

This state lasted until the fiftieth, when Iraq became independent; the protection of ancient monuments has become official policy of the authorities. Concerning Babylon, the publication /1/ states: "...Babylon belongs to all peoples and all nations. Visitors from all over the world are anxious that something should be done to further the restoration and reconstruction of Babylon's principal buildings, so that the city's former grandeur may be better appreciated."

In 1978 a broad plan for the protection of the most impressive ancient monuments, concerning the total country, was launched in Iraq /2/. As regards Babylon, this plan anticipated three types of activities:
- surveys of individual objects as basis for a competent future synthesis;
- development of some techniques (lowering of water-table, drainage and insulation of masonry constructions, conservation of clay bricks - dried and baked, production of bricks on site from salty clays, etc.);
- enlargement of old and construction of new museums on site.

Simultaneously, excavation works were carried out, as a return to or continuation of those of Koldewey.

Concerning the revival of the Tower of Babel, there were large differences in opinions and, therefore, this problem remained still open. The eventual rebuilding of the Tower was found to be preceded by careful "philosophic" analysis and advanced technical study, as well as - accumulation of large funds.

All those plans must have suffered considerably due to the Gulf War but the promotion of a policy friendly towards the restoration of Babylon, the Tower of Babel in particular, will always stay alive. This report is thought as a response to that challange. It concentrates on the Tower of Babel /3/, discussing especially some of its structural aspects, in terms of mechanics and strength of materials. May be it could contribute to the reconstruction of the Tower and of Babylon as a whole (Fig. 1).

2. BACKGROUND

It is commonly agreed that history /4/ and engineering /5/ were born in Sumer. Human civilization gained much through the emergence of the Sumerian city-states - at ca. 4500 B.C. Stage-towers, or ziggurats, were their most spectacular structures - later spread all over ancient Mesopotamia; the famous Tower of Babel is one of over thirty ziggurats discovered there until now.

Typical stage-tower was a gigantic, stepwise shaped, pedestal base carrying a temple at top. Together with a lower temple, it was for the Mesopotamians, most likely, the house of god and the gate of heaven. That idea is confirmed by all the ziggurats' names. In particular, E-temen-an-ki, standing for the Tower of Babel, means "House of the Foundations of Heaven and Earth."

"House" or "Foundation" are words articulating the engineering traditions of the Sumerians. Construction is deeply rooted in their past, as results from the Epic

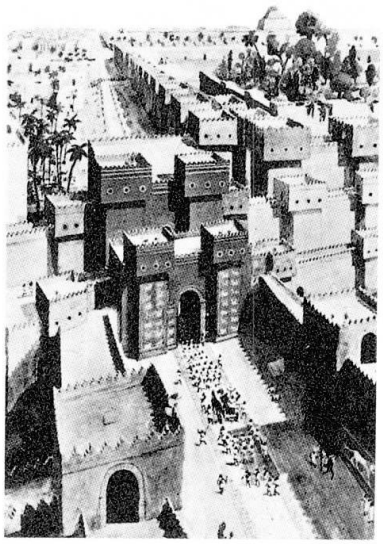

Fig. 1 Image of Babylon /1/

of Gilgamesh /6/ (Fig. 2). Ziggurats were built out of adobe and brick, since natural stone was scarce. The elements were simply placed and connected by clay or asphalt. Reed mats were applied at fixed levels of the ziggurat inner shafts - in order to achieve a better distribution of loading. Wooden anchors had to increase the stability of the ziggurat mantle walls. General impressions of the stage-towers, as seen originally by their builders, are given in Fig. 3 and Fig. 4.

"Examine the substructure,
view the brickwork.
Is the brickwork not of brick?
Did the Seven Sages
not lay the foundation?"

Fig. 2 Quotation from the Epic of Gilgamesh /6/

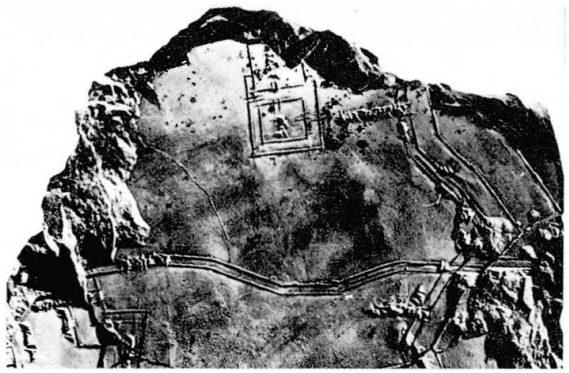

Fig. 3 Clay tablet with a stage-tower plan /7/

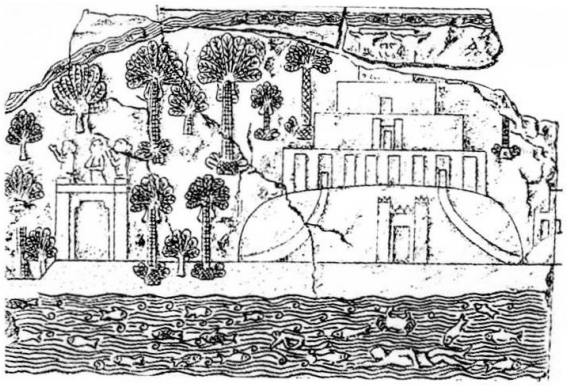

Fig. 4 Relief from Nineveh showing a stage-tower /2/

3. HISTORY

Biblical tradition caused that the Tower and the City of Babylon form certain entirety: "...as people moved eastwards they found a valley in the land of Shinar where they settled. They said to one another, 'Come, let us make bricks and bake them in the fire.' For stone they used bricks, and for mortar they used bitumen. 'Come,' they said, 'let us build ourselves a city and a tower with its top reaching heaven'" /8/.

Babylon or "bab-ilu" means "gate of god" /9/ (engineering implication of "gate" is evident). There are no data of archaeology on its genesis: high ground water level of to-day obstructs the penetration below the stratum of the 14th century B.C. Earliest cuneiform reference to Babylon as a secondary locality comes from the 21st century B.C. It appears that only during the Old Babylonian Period (ca. 1900-1600 B.C.) the city, with its god Marduk, became a weighty center of domination. But the construction of E-temen-an-ki was launched, probably, much later, when Nebuchadnezzar I (1123-1101 B.C.) was king of Babylon; when it was completed, is not certain /2/.

Babylon's conquest in 689 B.C. by the Assyrians caused that "the temple tower out of brick and earth", as mentioned by their king Sennacherib, was seriously destroyed /2/. But, for political reasons, already his son Esarhaddon and grandson Ashurbanipal tried to restore the Tower; first of them mentioned: "I ordered to rebuild the temple tower E-temen-an-ki on the old site 180 ells long and 180 ells wide" /2/. But the work must have not been much advanced at that time.

Only after the fall of Nineveh in 612 B.C. and the decline of Assyria, the victorious ruler of Babylon, Nabopolassar (625-605 B.C.) was able to speed up the reconstruction of the Tower. He wrote: "Concerning E-temen-an-ki, the stage-to-

wer of Babylon, that ... declined and laid in debris, Marduk, the lord, ordered me to consolidate its foundations within the bossom of underworld, and to make its top similar to heaven." He added, "I ordered baked bricks to be made. Since one had to consider abundant rains from heaven ... I commanded rivers of tar to be brought over the Arakhtu canal." His son, Nebuchadnezzar II (604-562 B.C.) finalized this work, recording: "All peoples of numerous nations I forced to work on the construction of E-temen-an-ki ... The high seat of Marduk, my lord, I prepared on its top ... I raised the top of E-temen-an-ki using baked bricks with bright blue glaze" /9/. Without question, it was the culmination of the Tower's splendour. Unfortunately, it ceased shortly thereafter, when in 539 B.C. Babylon was seized by the Persians under Cyrus II (559-530 B.C.).

During the Persian rule Babylon greatly deteriorated. Major destruction of the city was done by Darius I (522-485 B.C.) and Xerxes I (486-465 B.C.) /2/ - but the Tower of Babel continued to exist. By 460 B.C. it was seen by Herodotus, who reported: "In the center therin a powerful tower, one stadion in length and width, is built, and on that a second, thereon another and so altogether eight towers, always one above the other. Stairs are arranged on the outer side around all the tower" /9/.

Nevertheless, within years E-temen-an-ki must have suffered serious degradation, so that Alexander the Great, after taking Babylon in 331 B.C., decided to repair it. The related reference of Strabon (60 B.C. - 20 A.D.) is the following: "There was also the tomb of Bel, that, as said, was demolished by Xerxes. It was a foursided pyramid of baked bricks, being itself one stadion high, with each of the sides one stadion long. Alexander wanted to restore it, but the undertaking was enormous and required much time, since the removal of the ruins alone required the work of two months for 10,000 men, so that he was not able to complete the action started." Archaeological excavations have confirmed that report, uncovering a deposit with 300,000 cubic meters of Tower rubble, which corresponded to the 600,000 days of work mentioned by Strabon /2/.

The rule of the Seleucids (311-126 B.C.) introduced Seleucia as their capital, with which Babylon became secondary. In 140 B.C. it was captured by the Parths, what resulted in a serious depopulation of the city. By 199 A.D. Septimus Severus found it completely deserted /10/.

To-day there is only the trace of the Tower of Babel (Fig. 5), a very imperfect echo of the past glory (Fig. 6).

Fig. 5 Archaeological traces of the Tower of Babel /1/

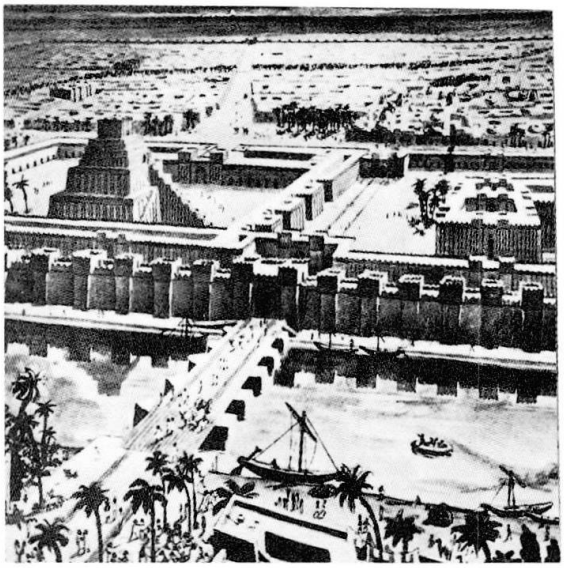

Fig. 6 Reconstruction of the Sacred Area (Temenos) in Babylon /1/

4. STRUCTURE

The typical feature of all the previously cited original notes on Babylon and its Tower was that they contained many references to engineering. Some of them concerned E-temen-an-ki's structure, especially the s.c. E-sag-ila Tablet /2/ - here until now left without a detailed analysis. Those descriptions are very important since, presently, only poor traces of the Tower could be found (Fig.5). Different scholars used these notes to develop their Tower images /3/ (Fig. 7).

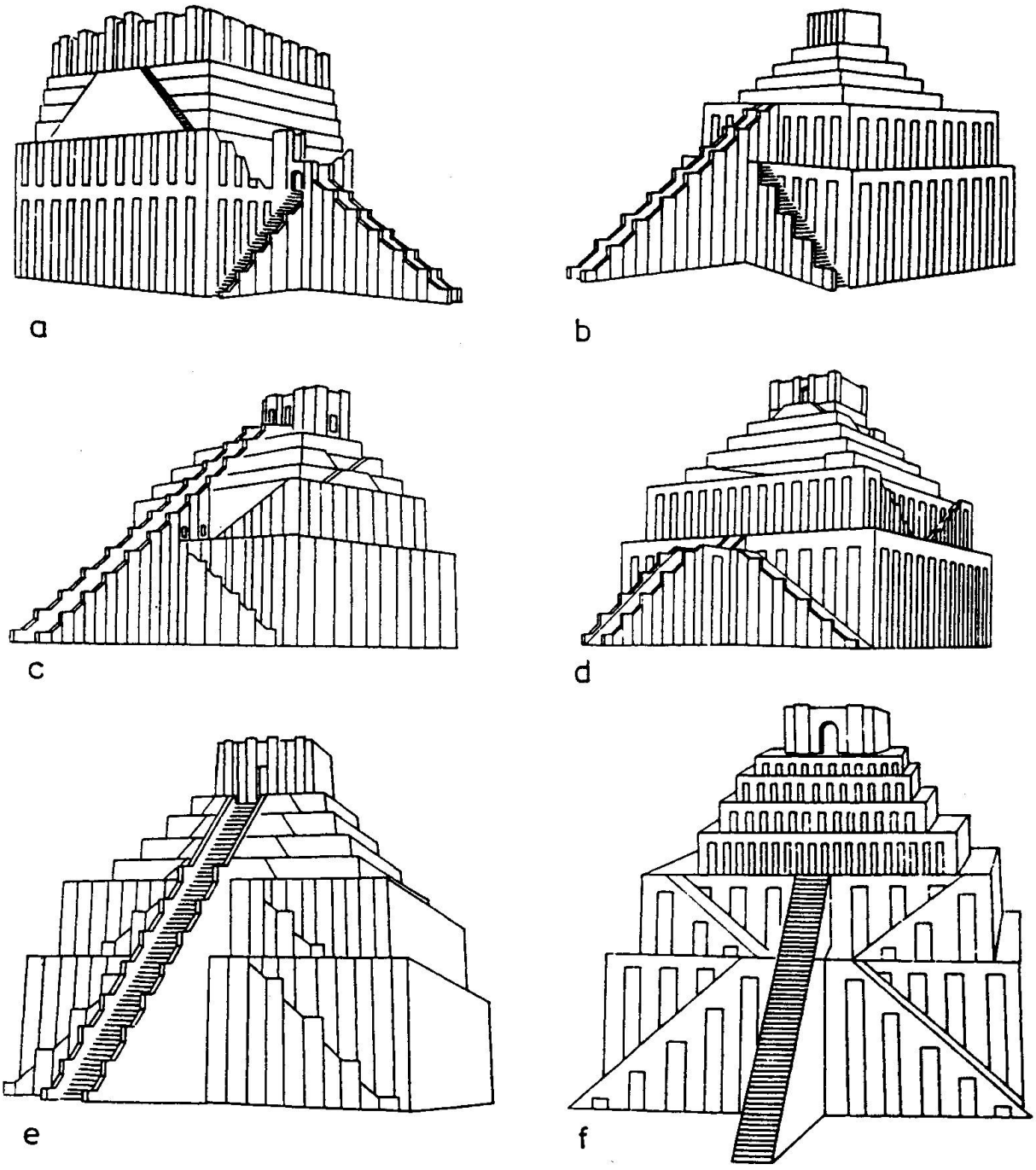

Fig. 7 Reconstructions of the Tower of Babel - by
a - Koldewey /2/ b - Dombart /2/
c - Andrae /2/ d - Busink /6/
e - Moberg /2/ f - Unger /2/

Using the original data of the E-sag-ila Tablet and applying the conversion of ell-dimensions into the metric ones, the most probable configuration of the Tower can be developed, as seen in Fig. 8 /3/.

The E-sag-ila Tablet notice about seven stories of the Tower is not conform with that of Herodotus, who reported eight (he must have regarded the foundation or one part of the double level top temple as separate stories), but both notices agree that E-temen-an-ki's length, width and height dimensions were equal. However, Herodotus, and later Strabon too, reported those dimensions to match one stadion (192.27 m - Olympic or 177.35 m - Delphic), what was just twice as much as in the Tablet. Since the Tablet data harmonize with those of Esarhaddon (180 ells = 91.55 m), and because they are conform with the findings of archaeology, author accepted the Tower dimensions as shown in Fig. 8 /3/.

The structural volume of the established shape was also point of research. According to /2/, the mature construction of E-temen-an-ki was that given by the vertical section of Fig. 8 a. Author of this report postulates the Tower structure to represent a co-operating composite of two main parts (Fig. 8 b):
- the square container like enveloping wall, constructed out of baked bricks connected by asphalt - being, according to the sexagesimal counting system of the Babylonians, in thickness one sixth of each story length, and
- the cased inner shaft made out of adobe and debris of former constructions, together with local sandy clay soil - everything with layers of reed inside.

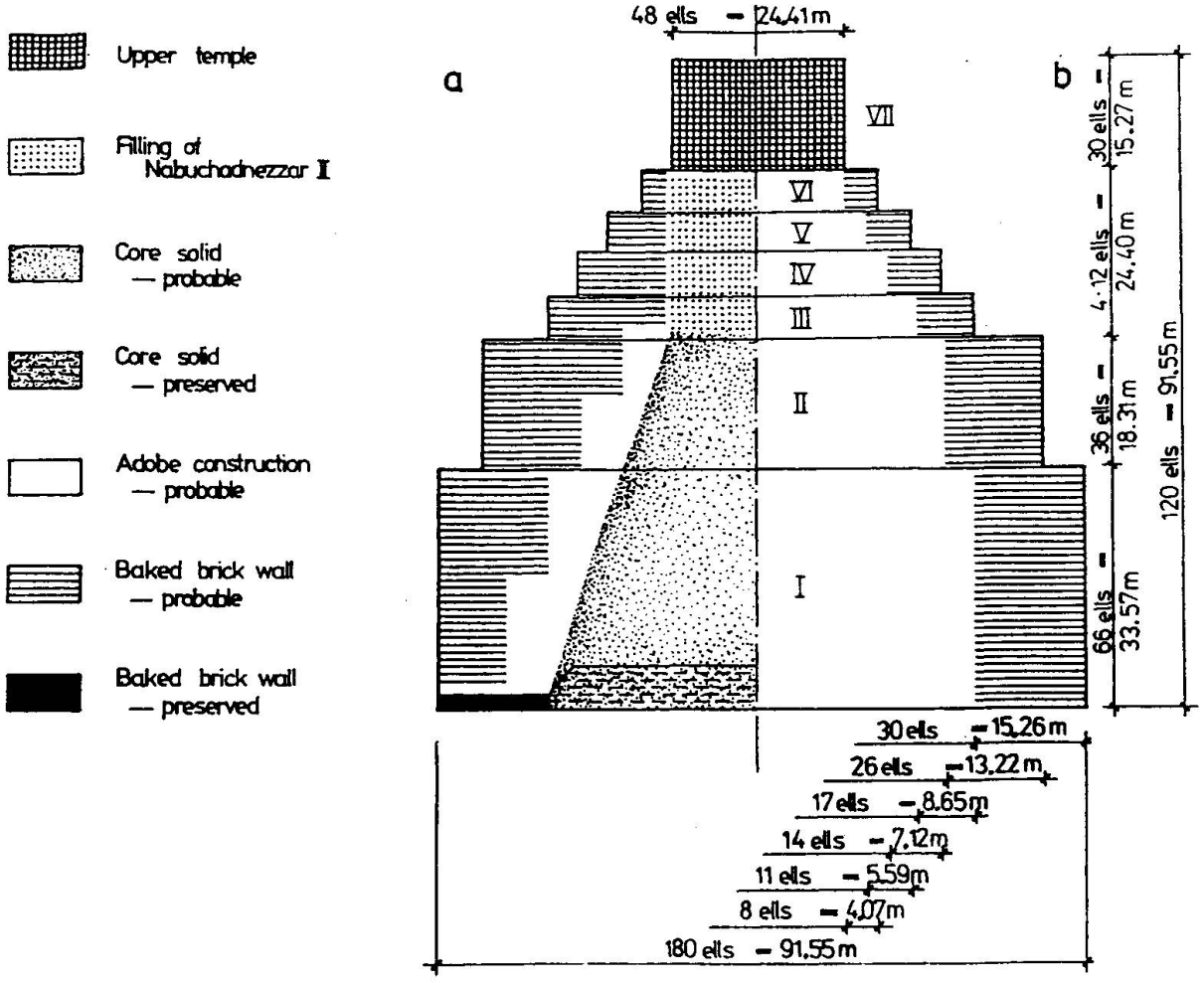

Fig. 8 Structural characteristics of the Tower of Babel - by
a - /2/ b - author

5. ANALYSIS

In order to approach the eventual reconstruction of the Tower of Babel, some basic technical parameters of its original construction should be determined. The main specification concerns the normal stresses (vertical pressures) σ at the bottom levels of the particular stories I-VII (Fig. 8 b) of the Tower. Assuming the volume specific gravity of its structural material as $\gamma=20$ kN/m^3, the stresses σ, supposed to be uniformly distributed, are the following /3/: $\sigma_I=305$ kN/m^2, $\sigma_{II}=273$ kN/m^2, $\sigma_{III}=291$ kN/m^2, $\sigma_{IV}=319$ kN/m^2, $\sigma_V=353$ kN/m^2, $\sigma_{VI}=575$ kN/m^2, $\sigma_{VII}=1103$ kN/m^2.

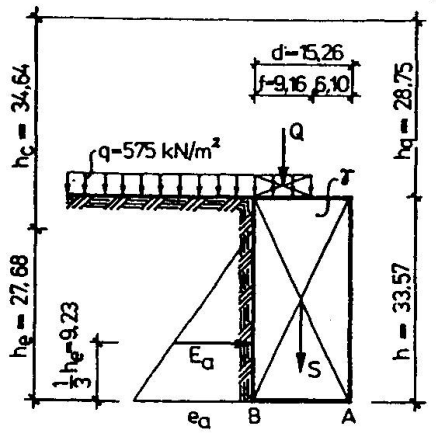

Fig. 9 Tower of Babel mantle wall analysis /3/

Another check should be referred to the ziggurat mantle wall (Fig. 9) /3/ - its strength and stability. The normal stresses at the bottom of this important structural element can be developed using the conservative system of a retaining wall, taking into account the dead load in question and the horizontal pressure of the inner shaft material. The concentrated vertical loads are the following:

$$P=Q+S=(q\cdot f+\gamma\cdot h\cdot d)1.00=5267+10246=15513 \text{ kN}.$$

The assumed angle of internal friction $\phi=30^o$ yields the factor of active earth pressure /11/

$$K_a=\tan^2(45^o-\phi/2)=1/3.$$

The depths of the fictitious soil layers, representing the surface loading q and the taken cohesion c=200 kN/m /12/, are

$$h_q=q/\gamma=28.75 \text{ m}, \qquad h_c=2c/\gamma\sqrt{K_a}=34.65 \text{ m},$$

respectively. Accordingly

$$e_a=\gamma(h+h_q-h_c)K_a=185 \text{ kN/m}^2, \quad E_a=0.5\cdot e_a\cdot h_e\cdot 1.00=2560 \text{ kN}.$$

Thus, the bending moment adequate for the rectangular unit bottom of the wall, is

$$M=E_a(h_e/3)-Q(d-f)/2=7565 \text{ kNm}.$$

The related cross-sectional area A and modulus of section Z are:

$$A=d\cdot 1.00=15.26 \text{ m}^2, \quad Z=1.00\cdot d^2/6=38.81 \text{ m}^2.$$

Correspondingly, the compressive stresses at the base edges A and B amount to

$$\sigma_A=(P/A)+(M/Z)=1212 \text{ kN/m}^2, \quad \sigma_B=(P/A)-(M/Z)=822 \text{ kN/m}^2.$$

Besides that, the Tower wall stability, i.e. rotation about A and sliding along AB (Fig. 9), should be verified. Concerning rotation, the resisting and disturbing moments are, respectively:

$$M_r=S(d/2)+Q(d-f/2)=134429 \text{ kNm}, \quad M_d=E_a(h_e/3)=23629 \text{ kNm},$$

and the related safety factor is

$$n_{rot}=M_r/M_d=5.69>\min.n_{rot}=1.25.$$

With the coefficient of friction $\mu=0.3$, the safety factor of sliding is

$$n_{sld}=\mu P/E_a=1.82>\min.n_{sld}=1.10.$$

Special interest should be paid to the settlements of the Tower, referred to the bottom of its lowest story /3/. Applying the central-point-method of /13/, with $\gamma=20$ kN/m^3, a=b=91.55 m, q=1103 kN/m^2 and the original oedometric modulus $M_o=50$ MPa, the maximum (uniform) settlement amounts to $\delta=1.034$ m, when neglecting the soil consolidation due to the Tower's repeated de- and construction in the past.

6. CONCLUSIONS

The performed engineering analysis of the supposed original structure of the Tower of Babel results in the following conclusions:

- The ratios of the stepwise shape did properly meet the option of equal own weight pressures only at the bottoms of stories VII to III; these pressures of ca. 300 kN/m^2 matched the safe bearing pressure for stiff clays /11/.
- The maximum own weight pressure of 1103 kN/m^2, found at the bottom of story I, considerably exceeds the safe bearing pressure of the local subsoil. Therefore, within ages, the calculated settlements of ca. 1 m must have occured. Thus, the customary consolidation of the ziggurat core structures, by reinforcing reed mats preventing structural disintegration, is understandable.
- The pressures at the foot edges A and B of the enveloping wall, amounting to 1212 and 822 kN/m^2 respectively, are also far above the safe bearing pressure of the local subsoil. Accordingly, in addition to the usual deflection associated with that of the core structure, the walls had a tendency of an outward rotation. Thus, the customary anchorage of the ziggurat walls, by wooden ties inside the trunk of the core structure, is understandable.
- The stability requirements regarding possible rotation and shift of the enveloping wall, in the conditions of rigid subsoil, were fairly satisfied. Thus, statically considered, the structural composition of the ziggurat core (adobe) and enveloping wall (baked bricks joined by asphalt), was safe.
- As stated, the settlements must have been very large and they could be met only by safeguarding the coherence of the ziggurat structure as a whole.

Concerning the anticipated rebuilding of the Tower of Babel, author suggests:

- a deep foundation to be built as a solid plate resting on piles, shafts or caissons, chosen according to the results of a reliable subsoil investigation;
- the properly shaped ziggurat structure to be made in box-type reinforced concrete, lined up by brickwork of high quality, well integrated with the former.

Such technically mature idea would, simultaneously, allow to utilize the closed space for the living needs of to-day.

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