COMBINATIONS OF ACTIONS AND PARTIAL COEFFICIENTS OF LARGE COOLING TOWERS

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1. Introduction

In this country, no sufficient experience on the design and construction of large cooling towers is available. This fact has induced the Ministry of Building and Urban Development to sponsor research in this subject in connection with the project of the Bicske thermal power station.

An item of utmost importance is the safety of these structures. In this respect, our major research results concerning

— the safety importance of large cooling towers;
— the combinations of actions;
— the design value of dead load;
— the design value of meteorological loads;
— the accidental actions;
— the potential stability of cooling towers

will be presented.

The relevant examinations followed the semi-probabilistic method specified in the Hungarian design standard MSz 15020—71 (recently MSz-COMECON 384—78). The semi-probabilistic method is known to rely on the analysis of limit states and to apply partial coefficients but here the partial coefficients and other parameters are interpreted in terms of the theory of probability, and the numerical values are determined by statistically processing national test data.

2. The safety importance of large cooling towers

The safety importance of so-called usual constructions under the validity of MSz-COMECON 384—76 is described by the damage ratio $\delta = 100$ to 125 [1]. In standard MSz 15020—71, the optimum failure probability belonging to this damage ratio is assumed to be $p = 10^{-4}$ [2]. Taking normality of the resultant distribution function into consideration, reliability index $\beta = 3.719$.

On the basis of these data, conditional equation of the semi-probabilistic calculus

$$(\gamma_R \cdot \gamma_S)^2 - 2(\gamma_R \cdot \gamma_S)\frac{1-2v_R}{1-\beta^2 v_R} + \frac{1-\beta^2 v_S^2}{1-\beta^2 v_R^2}(1-2v_R)^2 = 0 \tag{1}$$

where γ_R and γ_S — safety factors of resistance and load, resp.,
v_R and v_S — variation coefficients of resistance and load, resp.,
β — reliability index of the given failure probability p,

permits to determine safety factors [3].

Safety factors to be determined from (1) are included in the standard series MSz 15021/1 and MSz 15022/1. It is inadvisable to modify the safety factor in the design of constructions of higher or lower than average importance but a destination factor γ_n has to be introduced. The method for determining the destination factor has been described in [3].

The design standard for precast structures [5] contains the following numerical values:

— for structures where the failure involves no life danger but only minor material damages (e.g. vine props, fence posts), $\gamma_n = 0.9$;
— for usual structures, $\gamma_n = 1.0$;
— for structures where failure is likely to cause much higher than average damage (e.g. principal structures of a densely occupied building), $\gamma_n = 1.05$.

Research [4] on damages and material losses concomitant to the eventual failure of large cooling towers showed characteristic damage ratios

— in the construction stage: $\delta = 50$ to 55;
— in the final stage: $\delta = 30$ to 35.

Thus, damage ratios are lower for large cooling towers than for the usual buildings.

Dynamically, large cooling towers are less important than the usual structures, but obviously of an importance higher than $\gamma_n = 0.9$ for minor material losses according to [5].

This fact requires to closer determine the destination factor γ_n.

Determination of γ_n starts from the initial conditions:

— optimum failure probability [1]:

$$p_{RS} = \frac{1}{8_0 \cdot \delta} \tag{2}$$

— variation coefficients of resistance $v_R = 0.10$ and 0.15;
— variation coefficients of load capacity $v_S = 0.15$ and 0.10;
— resultant distribution function of resistance and stress **is assumed** to be of normal type;
— damage ratio of the failure of the large-size cooling tower complex
(i) in the construction stage $\delta_1 = 55$;
(ii) in the final stage $\delta_2 = 35$.

Based on these initial assumptions and making use of values in [2] leads to a reliability index β for large cooling towers

(i) in the construction stage $\beta_1 = 3.574$;
(ii) in the final stage $\beta_2 = 3.433$.

Solving conditional equation (1) for the product $\gamma_{RS} = (\gamma_R \cdot \gamma_S)$ with values β_1 and β_2, $\beta_0 = 3.719$ referring to a damage ratio $\delta_0 = 125$ resulted in Table I. Table parts I/C, I/A and I/B include product safety factors γ_{RS0}, γ_{RS1} and γ_{RS2} corresponding to $\delta_0 = 125$, $\delta_1 = 55$ and $\delta_2 = 25$, respectively. Destination factors referring to large cooling towers result from quotients of factors γ_{RS0} by γ_{RS1} and γ_{RS0} by γ_{RS2}, i.e. $\gamma_{n1} = \dfrac{\gamma_{RS1}}{\gamma_{RS0}}$ and $\gamma_{n2} = \dfrac{\gamma_{RS2}}{\gamma_{RS0}}$, respectively.

Table I

$(\gamma_R \cdot \gamma_S)$		V_R 0.10	0.15	0.20	0.25	
$\delta = 55$;			$\beta_1 = 3.574$			
v_S	0.05	1.279	1.529	2.117	4.704	A
	0.10	1.366	1.587	2.156	4.730	
	0.15	1.481	1.671	2.217	4.774	
	0.20	1.612	1.775	2.297	4.833	
	0.25	1.750	1.891	2.395	4.908	
$\delta = 35$;			$\beta_2 = 3.433$			
v_S	0.05	1.251	1.463	1.927	3.536	B
	0.10	1.334	1.518	1.964	3.561	
	0.15	1.445	1.599	2.023	3.603	
	0.20	1.569	1.698	2.099	3.659	
	0.25	1.701	1.808	2.188	3.729	
$\delta = 125$;			$\beta_0 = 3.719$			
v_S	0.05	1.309	1.604	2.356	7.127	C
	0.10	1.400	1.664	2.396	7.154	
	0.15	1.520	1.753	2.460	7.200	
	0.20	1.657	1.862	2.545	7.263	
	0.25	1.801	1.984	2.645	7.342	

Destination factors for the construction and the final stages γ_{n1} and γ_{n2} have been compiled in Tables IIC/A and IIC/B, respectively.

Table II

$\frac{(\gamma_R \cdot \gamma_S)_n}{(\gamma_R \cdot \gamma_S)_o} = \gamma_{ni}$		v_R 0.10	0.15	0.20	0.25	
$\delta = 55;$			$\beta_1 = 3.574$			
v_S	0.05	0.977	0.953	0.899	0.660	C/A
	0.10	0.976	0.954	0.900	0.661	
	0.15	0.974	0.953	0.901	0.663	
	0.20	0.973	0.953	0.903	0.665	
	0.25	0.972	0.953	0.905	0.668	
$\delta = 35;$			$\beta_2 = 3.433$			
v_S	0.05	0.956	0.912	0.818	0.496	C/B
	0.10	0.953	0.912	0.820	0.498	
	0.15	0.951	0.912	0.822	0.500	
	0.20	0.947	0.912	0.825	0.504	
	0.25	0.944	0.911	0.827	0.508	

Data in Table II show destination factors

— $\gamma_{n1} = 0.98$ to 0.95 for the construction stage,

— $\gamma_{n2} = 0.95$ to 0.91 for the final stage,

depending on the expected values of the variance coefficients v_R and v_S.

In compliance with the above, analysis of large cooling towers does not impose stricter safety measures than for usual buildings.

Eventually, if uncertainties of all essential parameters of importance for the load capacity are adequately reckoned with, then it is sufficient to apply a destination factor of the quoted order, and to comply otherwise with specifications in standard series MSz 15022. Since, however, reliability of wind load data is below the average, at a difference from this rather accurate close calculation, the more favourable damage ratios are advisably ignored to consider large cooling towers as constructions not different from conventional ones.

3. Combinations of actions

Combinations of actions on load-bearing structures of constructions under the validity of MSz 15022—71 — interpreted for large cooling towers — will be determined as follows.

The combination of actions can be written as:

$$F_d = \gamma_n \left[\Sigma G + \left(V_1 + \sum_{i=2}^{n} \psi_i V_i \right) \gamma_{n0} \right] \tag{3}$$

where ΣG is the permanent load on the structure, V is a live load. Checking the non-catastrophal ultimate condition of stiffness and cracking has to involve the initial values, while for catastrophal (load capacity, potential stability) ultimate conditions, extreme values have to be applied.

V in (3) has been defined in MSz 15021/1 as:

V_1 — outstanding live load,

— in general, the working load, or, in case of several working loads, that with the worst effect;

— in lack of a working load acting on the structure, or if its effect is much superseded by some meteorological load, then the most adverse meteorological or other load has to be reckoned with;

— if extraordinary loads intervene in analysing the structure, then as an alternative to reckoning with the combinations of extreme actions, preference given the extraordinary load has to be examined.

Coefficient ψ_i in (3) may be integrated, according to research made at the Department of Reinforced Concrete Structures, [7], as:

ψ_i — combination factor, with values:

— in general:

— for permanent, live loads	0.8
— for instantaneous live loads	0.6
— for accidental live loads	0.0

— on account of seismic effects as outstanding live loads:

— for permanent live loads	0.8
— for instantaneous live loads	0.0
— for other accidental loads	0.0.

Again, in Eq. (3),

γ_n — destination factor, of a value to be selected according to Chapter 2;

γ_{n0} — destination factor to be applied for live loads on temporary buildings designed for at most 5 years of service life.

Analysis of large cooling towers has to involve primarily the permanent loads, including dead load, constructional stresses, meteorologic loads and extraordinary loads.

Let us review now the aspects of reckoning with these loads.

4. Design dead load values

4.1 Dead loads

It is advisable to apply a method more accurate than usual relying on standard specifications MSz 510—77.

The dead load is known to be the product of mass M_2 [kg] of the given building material or structure by gravity acceleration $g = 9.81$ m/sec^2. The solid mass is product of solid density ϱ [kg/m^3] by volume V [m^3].

Thus, dead load of the structure:

$$G = M \cdot g = \varrho \cdot V \cdot g \ [\text{kg m sec}^{-2} = N].$$

4.2 Determination of the solid density

Mean values and standard deviations for various building material densities are found in the standard MSz 510—76 "Mass and solid density of building materials and building structures" [8].

Thus, solid density of a concrete made with sand and gravel aggregate:

Grades B 50 to B 200:

mean	$\varrho_m = 2000$ kg/m^3
standard deviation	$s_\varrho = 100$ kg/m^3

Grade B 280:

mean	$\varrho_m = 2300$ kg/m^3
standard deviation	$s_\varrho = 140$ kg/m^3

Grade B 400:

mean	$\varrho_m = 2400$ kg/m^3
standard deviation	$s_\varrho = 140$ kg/m^3.

Solid density of reinforced concrete is composed of the solid density of concrete increased by the really incorporated steel reinforcement, but at least by 100 kg/m^3 higher than the respective values.

Solid density of moist concrete has to be increased by 50 to 150 kg/m^3 depending on its absorptivity. It is advisable to weigh the solid density of concrete for cooling towers, namely the slip-form building system may cause loosening of the concrete.

Extensiveness of cooling tower walls permits to reduce the standard deviation of concrete solid density as:

$$s_{\text{red}} = s_\varrho \sqrt{0.25 + \frac{0.75 V_0}{V}} \qquad (4)$$

where $V_0 = 1.33\ \text{m}^3$;
V = volume of the solid above the examined section [m^3];
s_ϱ = standard deviation defined above.

4.3 Basic and extreme mass values

Basic value of the cylindrical wall:

$$M_m = V_m \cdot \varrho_m \tag{5}$$

its extreme value (assuming normal distribution):

$$M_u = M_m \pm 1.64\, s_M \tag{6}$$

where V_m — volume above the examined section determined from average geometry values;
ϱ_m — expected (mean) solid density value;
s_M — derived standard deviation of the mass, to be calculated from (7) for circular symmetric walls of cooling towers.

Standard deviation has been derived for the mass $M_m = 2r \cdot \pi \cdot h \cdot H \cdot \varrho$ of a cylindrical wall height H over the examined section as:

$$s_M = 2\pi \sqrt{(h \cdot H \cdot s_r)^2 + (r \cdot H \cdot s_h)^2 + (r \cdot h \cdot s_H)^2 + (r \cdot h \cdot H \cdot s)^2} \tag{7}$$

where r — mean radius of the annular section;
h — wall thickness of the circular ring;
s_r — standard deviation of the radius;
s_h — standard deviation of the wall thickness;
s_ϱ — standard deviation of solid density;
H — length of the meridional section of the solid above the examined annular section.

5. Design meteorological load values

The position of the Department on the basic values of wind and other meteorological values to be reckoned with as instantaneous loads according to MSz 15021/1 and their dynamic effects has been described in other papers in this issue.

Safety factors γ_v to be adapted in determining extreme values of meteorological loads:

— for wind loads $\gamma_w = 1.2$
— for temperature loads $\gamma_t = 1.2$
— for snow loads $\gamma_s = 1.4$.

The standard series MSz-COMECON permits lower meteorological load values to be reckoned with in the construction stage.

Tests have shown that, in lack of exacter probabilistic considerations,

— for a construction time not exceeding one year, the value of destination factor [3] $\gamma_{n0} = 0.8$;
— for construction times between one and five years, $\gamma_{n0} = 0.9$ may be taken.

6. Accidental loads

Cooling towers may be exposed mainly to seismic effects as accidental loads.

The special working group at the Department has suggested the following procedure in this respect [7]:

— On sites in seismic belts of intensity VI or higher according to scales MCS (Mercalli—Cancani—Sieberg) or MSK 64, safety to seismic effects has to be reckoned with as an inherent requirement.
— Else, half percent of the design values of the construction dead load has to be considered as extreme value of the horizontal mass force of arbitrary direction. Distribution of the horizontal mass force corresponds to the distribution of masses. (This load value will be involved in Eq. (3) as an outstanding live load.)

Particulars of the analysis for seismic effects (taking horizontal and vertical acceleration into consideration) will be presented in a special study.

7. Examination of potential stability

Examination of the potential stability of cooling towers involves checking of condition

$$\frac{R_u}{F_u} \geq \gamma_R = 1.0 \tag{8}$$

where R_u and F_u are extreme values of combined actions favourable or injurious to potential stability, with the difference that the lower threshold value of loads intervening in R_u has to be multiplied by 0.9. For instance, design value of the mass of the wall structure decisive for the stability becomes, according to (6):

$$M_u = (M_m - 1.64\, s_M)\, 0.9\,. \tag{9}$$

Summary

Some problems relevant to the safety of large cooling towers have been considered. Fundamentals of standard MSz-COMECON 384 have been expounded. Determination of the destination factor related to the safety importance of cooling towers, as well as definition of the design combination of actions have been presented.

A method has been presented for the determination of basic and extreme values of major load types — including dead load, — and for checking the condition involved in the examination of potential stability. Both final and transitory building stages have been reckoned with.

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