Simulation of fitting of construction organizations and erected buildings with collective protective equipment

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Abstract. They provided the procedure of planning of fitting of construction organizations, performing the construction of multistory buildings of various applications, with effective collective protective equipment, and also determining the required volume of such protective equipment directly at the erected projects. Principle of the method is based on such indicators of projects, erected construction organizations, as types and areas of buildings, standard construction time and some other values. Determination of requirement in collective protective equipment for a definite building is proposed at the lowest cost taking into account specific indicators, based on configuration and number of stories of the erected building, set of the applied construction structural components, standard operating procedures and other factors. Simulation of fitting of erected buildings with collective protective equipment envisages the task solution with application of generic potential method at the principle of optimum allocation. They take into consideration a maximum amount of collective protective equipment, which a construction organization can have in the planned period of time, taking also into account a possibility of their additional production or supply by third party enterprises. Determination of the quantitative composition of the units of the required construction of collective protective equipment, which are to be applied at the project, is performed based on the condition that expenses for production and allocation of these equipment will be minimum.

1. Introduction

Increasing the number of stories of erected buildings and correspondingly increasing the volume of construction and erection work, performed at height, complication of technological processes requires application of a certain assortment of technical safety features [1], and first of all providing collective protection.

Collective protection features during performance of construction and erection work at height include devices designed for:
- isolation of working places at height and accesses to them;
- preventing of unintentional access of a man to an edge;
- holding a man in case of loss of balance and virtual fall from height;
- designating of danger zones, within which there is a danger of fall from height;
- installation of isolation within the working place until the edge;
- installation of catching devices outside the working place;
- disposition between supports or vertical surfaces of building civil structures.

During building erection one can apply various collective protection features to prevent a man fall as a safety barriers of working places at height and accesses to them, disposition of main protective components vertically is their main pacing factor. Such collective protection features include safety protection which serve for prevention of unintentional access of a man to an edge. Besides, near edge one can apply safety guards designed to keep a man in case if he losses a balance, and also signaling guards to mark a danger zone of virtual fall from height. [2]

Depending from disposition the protective guards can be:
- internal – installed within the working place and work sites until edge;
- outer – installed outside the working place near the edge.

The protective guards with vertical disposition of main protective components got the widest application in preventing man from falling from height. In such protective features on can mark out the following structural members - details, assembly units (nodal points), sections and packages.

Details in protective features are goods, performing certain function and produced of uniform in structure and properties material, providing the established requirements independently or constituting a part of assembly unit (support, screw, stand and others).

Assembly unit – a nodal point, consisting of details, connected between themselves as a result of the performed assembly or other industrial operations (clamp, collar and other), comprising a part of section.

Section in collective protection features is a group of interconnected details and assembly units, providing the required operation functions on provision of safety operation (protective, backfit and warning fences).

Package – two and more sections, designed for joint performance of operation functions of collective protective equipment during erection of buildings and structures (fence of floor openings, building perimeter fence and other).

2. Literature review and accumulated experience analysis
The results of analysis of construction industrial traumatism display that the biggest amount of accidents during performance of construction and assembly operations is connected with falling of men and objects at a man from height during buildings erection. Examination of materials of investigation of such cases gives a possibility to ascertain that industrial traumatism reduction can be provided as a result of solutions made based on development of measures comprising work execution designs (WED) and flow diagrams (FD), providing application of collective protective equipment.[3]

At this a certain influence at selection and volumes of protective features are made by such factors as type of erected building, types of operations, conditions of their execution, probable extent of application of one or another technical safety features and other.

In construction production they apply protective guards, which structures use rolled steel, board lumber, steel ropes, synthetic and metal meshes.

Protective guards of rolled steel in domestic and foreign construction practice represent the most common group of collective protective equipment from height fall. They can be attached to lifting eyes and but end of floor slabs. The governing of this type of guard is that all main components are produced of rolled steel. Such structures excel high reliability, but require big amount of steel consumption.

Board lumber in organizational protective guards are used, as a rule, as horizontal components and guard board. Protective guards, where board lumber is used, are easy in manufacture, but wood application is limited by its still increasing cost and reduction of qualitative factors in the course of operation.

Steel ropes in protective guards are applied most of all for designation and warning of access to danger area during execution of construction and assembly operations. Possibility to apply the ropes in collective protection features is restricted by necessity to make big efforts for their pulling, which are
also transferred to the structures which they are attached to, and necessity of availability of additional special pulling device.

Synthetic and steel meshes with cell to 100 mm serve as protective shield, located between guard supports or vertical building civil structures. At this application of steel meshes increases the weight of protective guards, and synthetic meshes, despite their prospects of wider application, require special operation conditions.

3. Methods, system simulation and results
Taking into account that nowadays there is a various nomenclature of collective protective equipment with various technical and economical factors, but having similar fields of application, the selection of the most optimum protection features taking into account certain factors is quite a crucial task.

The criterion of optimum allocation and planning of fitting with protective features are minimum costs upon condition the required safety level for the planned period of the object erection. [4]

Construction departments directly performing construction and assembly operations at height of erected buildings, but not performing production of protective features, shall have available or a possibility to acquire to provide the required safety level a certain amount of collective protective equipment. In such conditions it is possible to apply a simplified method of determining of required volume of protective features for construction organization. The essence of this method lies in application of the factor of specific length \( k_{yj} \), which is determined from correlation [5]

\[
k_{yj} = \frac{P_{yj}}{S_{yj}} , \tag{1}
\]

where \( P_{yj} \) – perimeter of one-story building, m;
\( S_{yj} \) - area of one story of building, m².

Having processed the initial data on the most erected and types of buildings, and also structural solutions of such buildings taking into account the length of their perimeter and number of storeys, availability of virtual openings inside the very buildings, they determined the specific factor of length \( k_{yj} \), which made up for buildings of insitu reinforced concrete \( 0.22 \), frame-panel – \( 0.2 \), large panel – \( 0.243 \), brick – \( 0.26 \).

The informational basis of calculation method of the required volume of protective features comprised application of such the most known and available initial data as total area of commissioning of construction objects in the planned period, type and series of buildings, number of storeys, standard or estimated time of its buildings erection, annual reserve of labor time. Total annual area of commissioning \( S_{ob} \) can be formed of construction of buildings of various types

\[
S_{ob} = \sum_{j=1}^{n} S_j \tag{2}
\]

where \( S_j \) – annual area of commissioning - type of building.

For each type of building the area of commission can be determined from correlation

\[
S_j = N_j \cdot k_{yj} \cdot S_{yj} , \tag{3}
\]

where \( k_{yj} \) - number of storeys \( j \)-the type of building;
\( N_j \) – number of erected buildings of \( j \)-th type;
\( S_{yj} \) - area of one storey of \( j \)-th type of building.

Hence

\[
S_{yj} = \frac{S_j}{N_j \cdot k_{yj}} . \tag{4}
\]

The duration of erection of one \( t_{yj} \) type of storey equals

\[
t_{yj} = \frac{t_j}{k_{yj}} , \tag{5}
\]

where \( t_j \) – standard duration of aboveground building part erection.

Based on the fact that operation performance intensity is performed rhythmically, it is possible to set a correlation
\[ S_j = \frac{S_{ij}}{t_g}, \quad n_{ij} = \frac{t_g}{t_{ij}}, \quad (6) \]

where \( n_{ij} \) – amount of simultaneously erected storeys of building of \( j \)-type; \( t_g \) – annual reserve of labor time.

From correlation (4), (5) and (6) we get correspondence

\[ n_{ij} = N_j \frac{t_{ij}}{t_g} k_{ij}, \quad (7) \]

showing the extent of construction and assembly operations development.

Annual requirement in \( i \) – features of protection for \( j \)-th type of building will equal

\[ V_{ij} = n_{ij} * r_{ij} * k_{ij}, \quad (8) \]

where \( k_{ij} \) – coefficient of rational saturation of \( j \)-th type of building with \( i \) – feature of protection. Based on technology of pro standard operations procedure for site-cast concrete and frame-panel buildings \( k_{nij} = 2 \), and for large panel and brick buildings \( k_{nij} = 1 \).

From correlation (4), (7) and (8) we shall get formula

\[ X_{ij} = k_{ij} \cdot k_{nij} \frac{s_{ij}}{t_g l_{ij} k_{ij}}, \quad (9) \]

which determines the duration of protection features for \( j \)-th type of building. Having divided the value of formula (9) into the length of one section \( l_i \) one can calculate the required amount of features \( X_{ij} \) for \( j \)-th type of building

\[ X_{ij} = k_{ij} \cdot k_{nij} \frac{s_{ij}}{t_g l_i k_{ij}}, \quad (10) \]

4. Results

Taking into account the saturation coefficient, depending on the required level of protection of danger zone at working place and type of erected building and also specific duration, it is possible to provide a composite index of protection features for various types of buildings. As a result it is possible to ascertain the amount of protection features for buildings:

with site-cast concrete framing

\[ X_{im} = 0.44 \frac{s_{ij}}{t_g l_i k_{ij}}, \quad (11) \]

frame – panel buildings

\[ X_{ip} = 0.4 \frac{s_{ij}}{t_g l_i k_{ij}}, \quad (12) \]

large panel buildings

\[ X_{ip} = 0.243 \frac{s_{ij}}{t_g l_i k_{ij}}, \quad (13) \]

brick buildings

\[ X_{ik} = 0.26 \frac{s_{ij}}{t_g l_i k_{ij}}, \quad (14) \]

Thus, knowing a standard or calculated duration of objects construction and working time reserve, it is possible to simplify the order of determination of the required amount of collective protective equipment for construction organizations for a certain period.

To determine the requirement in protection equipment during erection of definite buildings it is possible to apply two ways of calculation: [1]

- for 1 mln. r. of construction and erection work;
- on specific duration of the installed protection devices.
The first way is more generalized and does not take into account the volume and planning solutions of the object and peculiarities of industrial processes of its erection. This way is the mostly appropriate on determination of requirement in protection means during long-term planning for construction organizations with large volumes of operations.

More rational way, giving a possibility for definite types of objects to determine the requirement in protection devices on specific indeces, where they take into account building configuration, number of storeys, applied structural components, standard operating procedure and other. Taking into account these factors, they propose the method of calculation of requirement in protection equipment for construction organizations of various level and types of erected objects. [6]

As above for calculations we shall take that for each type of building they set a definite, required to provide the requested safety of operations, volume of application of protection equipment at j-th object \( V_j \geq 0 \), at that j =1,……n. We shall set also annual costs for application of a unit of volume of the applied i-th protection equipment (1 running meter) i=1,……m from condition \( C_{ij} \geq 0 \) (roubles per 1 running meter).

Matrix of “possibilities” of application of i-th structure of protective means at j-th object we shall present in the form of \( S_{ij} \), at this \( S_{ij}=1 \), if protection mean can be applied at j-th object and \( S_{ij}=0 \) in case it is impossible to apply at a this object. It is required to find values \( X_{ij} \) – number of units (running meters) of protection means of i-th structure, which is to be applied at j-th object, upon condition that costs for production and allocation of all protection means will be minimum. Mathemetic model of the set task looks in the following way. [4,5]

It is known that in the planned period the construction organization can erect buildings of various types. For each type of buildings they know the required volume (total length) of collective protection means \( V_j \), j =1,……n, where n – number of possible types of buildings. The construction organization has a certain amount of collective protective equipment of various structures \( a_i \) i=1,……m, where m – number of various structures of protective equipment. It is also known that maximum amount of collective protective equipment, which can be possessed by construction organization in the planned period taking into account additional their production (supply). [7,8]

It is required to determine the optimum distribution on the erected buildings of the available means of collective protection and also volume of their additional production. [9]

It is required to pay a special attention to the following circumstance, namely, if during erection of building of such type one can apply various structures of collective protective equipment, then it is supposed that from the point of view of their functional application they are the same, i.e. at the same level provide the similar level of safety of performance of construction and assembly operations at height. Otherwise the priority is given to that structure of protection device, which provides a higher safety level.

To resolve the task it is required the annual costs \( C_{ij} \) for application of one meter of i-th structure of collective protective equipment at building of j-th type. Then one shall take into account that in the course of construction the collective protective equipment can be moved, i.e. one meter of protection equipment during a year performs the scope of works of more than one meter. This cope of works \( P_{ij} \) shall also be determined. Hereafter we shall call it annual performance of i-th collective protection mean at j-th type of buildings. [10,11]

Determination of values \( C_{ij} \) and \( P_{ij} \) are proposed to be performed according to the following formulae:

\[
C_{ij} = \frac{U_i}{t_{ij}} + (Z_{mij} + N_{ij} + Z_{m}) \frac{T_g}{(t_{m} + t_{m})} ;
\]

\[
P_{ij} = \frac{N_{ij} T_g}{t_{m} + t_{m}} ;
\]
where $U_i$ - cost of one meter of $i$-th protection equipment, $r/m$;
$t_{ij}$ – operation service life of $i$-th protection equipment at $j$-th building per year;
$Z_{mij}$ - costs for assembly-disassembly of one meter of $i$-th protection equipment at $j$-th building, $r/m$;

$N_{ij}$ - number of moves of $i$-th protection equipment at $j$-th building;
$Z_{m}$ - costs for relocation of one meter of $i$-th protection equipment from one erected building to another, $r/m$;

$T_g$ - annual reserve of labor time, $h/year$;
$t_{bi}$ – erection time of object of $j$-th type, $h$;
$t_{ni}$ – time for relocation of $i$-th protection equipment from one construction building to another, $h$.

Values $t_{ij}$ and $Z_{mij}$ can be determined according to formulae

$$t_{ij} = \frac{N_{\text{max}}}{N_{ij} T_g} (t_{bi} + t_{ni}) \quad ;$$

$$Z_{mij} = M_i l R, \quad (17)$$

where $N_{\text{max}}$ - maximum amount of relocations of $i$-th protective mean;
$M_i$ - weight of one meter of $i$-th protective mean, kg;
$l$ - average distance of relocation of $i$-th protection equipment from one construction building to another, km;
$R$ - rate for relocation of loads (protection means), $r/kg$. $m$.

5. Discussion

Actual sense of the provided indeces includes specific features of technical parameters, generocity, transportation ability, easy of assembly-disassembly, reliability and simplicity in operation, longevity. [12,13]

If we present $X_{ij}$ as amount of protection means of $i$-th structure at objects of $j$-th type, then for determination of $X_{ij}$ ($i=1\ldots m$, $j=1\ldots n$) from condition of minimum of provided costs

$$m \quad n \quad \sum_{i=1}^{m} \sum_{j=1}^{n} C_{ij} X_{ij} \rightarrow \min,$$

in case of restrictions

$$m \quad \sum_{i=1}^{m} P_{ij} X_{ij} = V_j \quad (j=1\ldots n),$$

$$n \quad a_i \leq \sum_{j=1}^{n} X_{ij} \leq b_i \quad (i=1\ldots m).$$

Restrictions in formula (20) are conditions of performance of all scope of works, and restrictions in formula (21) – conditions of application of existing collective protective equipment and restrictions for their supply (production), i.e. $b_i$ – possible annual volume of production (supply) of $i$-th protection mean. At this one shall take into account that not all protection equipment fit for execution of certain types of construction and assembly operations.

If $i$-th protection equipment can not be used at the object of $j$-th type, then corresponding values $C_{ij}$ is taken quite big, and $P_{ij}=1$ in accordance with the entered matrix $S_{ij}$.

Because of big diversity of structures of collective protective equipment, applied nowadays in construction, the amount of task variable $X_{ij}$ is quite big, as a result the use of general method of resolving such tasks applying simplex-method does not seem appropriate.
The general potential method (method of allocation task resolving) is taken as a basis of method of resolving of the task under consideration, which is a modification of simplex-method and consists of two stages. [14]

At first stage they perform a control of allocation for optimality, and at the second – allocation improvement, if it is not optimum. Multiple repetition of these stages gives a possibility to obtain an optimum allocation.

Algorithm of common method of potentials is described in works. [4, 5] To take into account two-sides restrictions, provided in formula (21), some amendments are put into the method. Possible algorithm of method envisages additional matrixes of allocation of $n + 1$ columns, which variable transfer restrictions of formula (21) into equations

$$\sum_{j=1}^{n} X_{ij} + X_{i,n+1} = b_i \quad (i=1 \ldots m) \quad (22)$$

Method modification lies in introduction of throughput abilities for variables of $n + 1$-th column $X_{i,n+1} \leq a_i$.

At this one should note that this modification make some influence at calculations in both stages of method, and also at preliminary calculations on determination of starting basis.

6. Conclusions

Increasing of construction volumes of high-rise buildings and correspondingly construction and erection works, performed at height and at this complicating of technological processes, is connected with the growth of cases of industrial traumatism because of falling of men and objects at men from height, due to this in order to improve occupational safety it is required to apply a collective protective equipment, envisaged by organization and technological documentation.

Key condition of effective application of collective protective equipment is determination of required volume of such protection means at the level of construction organizations taking into account objects construction schedule for a certain period and fitting with them of the erected buildings in the amount that is sufficient to provide the required level of operations safety.

For definite objects the most rational way to determine the requirement in protection means is an application of indexes, taking into account number of storeys, applied structural components, building configuration, operation production technology and some other indexes.

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