

**A FRAMEWORK FOR OPTIMIZATION OF TIME AND
COST CONSIDERING SAFETY IN SHORE-RESHORE
DECISION FOR CONSTRUCTION OF FLAT SLABS IN
A MULTI-STOREY BUILDING**

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A FRAMEWORK FOR OPTIMIZATION OF TIME AND COST CONSIDERING SAFETY IN SHORE-RESHORE DECISION FOR CONSTRUCTION OF FLAT SLABS IN A MULTI-STOREY BUILDING

by

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CERTIFICATE

This is to certify that the thesis entitled, “**A Framework for Optimization of Time and Cost considering Safety in Shore-Reshore Decision for Construction of Flat Slabs in a Multi-Storey Building**” being submitted by **Mrs. Prachi Kaustubh Sohoni** to the Indian Institute of Technology Delhi for the award of the degree of ‘**Doctor of Philosophy**’ is a bonafide record of research work carried out by her under my supervision and guidance. The thesis work, in my opinion, has reached the requisite standard fulfilling the requirement for the degree of Doctor of Philosophy. The results contained in this thesis have not been submitted, in part or full, to any other University or Institute for the award of any degree or diploma.

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ABSTRACT

Multi-storey building construction is moving at a faster rate. The tendency of a builder is to complete the construction in the shortest possible time and the least possible cost. Formwork, being an important component of reinforced concrete (RC) construction, plays an important role in the construction of a multi-storey RC building. The horizontal formwork constitutes components such as sheathing members, joists, stringers, and single-leg shores or multi-leg shores depending on the condition.

The safety of the structure during construction depends on the load transfer mechanism from slab to shores, making these components important in the horizontal formwork system. The selection of shores requires careful consideration and effective usage to ensure the safety of the structure during construction. To achieve this aim, six different objectives were identified. These are: (1) to evaluate factors for shores selection in multi-storey building construction, (2) to analyze the loads on slabs and shores-reshores in multi-storey RC building construction, (3) to optimize the time of RC work in a multi-storey building, (4) to optimize the cost of RC work in a multi-storey building, (5) to optimize the time and cost of RC work in a multi-storey building by maintaining safety during construction, and (6) to evaluate the shore loads with respect to shore spacing and shore removal pattern. Various analysis and evaluation tools such as principal component analysis (PCA), analytical hierarchy process (AHP), and genetic algorithm (GA) were used to achieve these objectives.

For shores selection, the attributes relevant to both single-leg shores and multi-leg shores were considered. These attributes were compiled from a literature review and discussion with experts. This resulted in a total of 14 attributes for single-leg shores, while 21 attributes were compiled for the selection of multi-leg shores. The application of principal component analysis (PCA) has extracted five factors from the 14 attributes for single-leg shores and seven factors from the 21 attributes for multi-leg shores selection. The five factors for single-leg shores selection were: (1) shore characteristics, (2) convenience in shore placement, (3) cost of shore, (4) availability of shore in the required quantity, and (5) reusability of shore. The seven factors for multi-leg shores selection were: (1) tower shore characteristics, (2) intrinsic characteristics of tower shore, (3) availability of tower shore in the required quantity, (4) ease of shore placement,

(5) shore connection and installation equipment, (6) cost of shore, and (7) reusability of shore. These factors were further evaluated for their relative ranking using the analytical hierarchy process (AHP). A framework was further developed to help the decision-maker in selecting the shores from among the available options.

Subsequent to the selection of a proper system of shores for a project, the analysis for the load distribution among the slabs, shores, and reshores during construction of a multi-storey building becomes important from the safety point of view. For this, a computational program was developed considering the simplified method (developed by Grundy and Kabaila (1963)) to study this load distribution. The analysis was carried out for three different geographic locations, i.e. India, USA, and Europe, as the formulae used for the concrete strength development are different here. It was observed that the strength gained by the slab with respect to the elapsed time was the highest for Europe, followed by USA, and then by India based on the type of cement, method of curing, and strength calculation equation. A graphical user interface (GUI) was also developed by considering the construction sequence for RC buildings to help the users in comparing the safety of the structure by varying the different parameters such as number of levels of shores-reshores, cycle time, stripping time, grade of concrete, etc.

The formwork needs to be removed as early as possible because it takes the major proportion of the total cost of construction and plays a key role in achieving the construction time. Hence, the developed computational program for load distribution among the slabs and shores-reshores was modified with a GA to optimize the time of RC work. The objective function was derived considering the time and safety parameters. It was found that a minimum M30 grade of concrete is required for speedy construction by maintaining minimum safety requirements. The optimization of the cost of RC work was carried out considering the construction of slabs in a multi-storey RC building by maintaining the safety of the structure. The objective function was developed with the number of levels of shores, the number of levels of reshores, the grade of concrete, and the overhead charges. The lower grades of concrete, such as M20 to M30, violate the safety condition for some combinations of levels of shores-reshores. It was suggested to use more levels of reshores than levels of shores to minimize the cost of RC work by maintaining the safety of the building. Further, the time and cost of RC work were optimized simultaneously. The previously derived functions of time and cost were combined

together by the priori approach, and the optimization was carried out by assigning different priority weights to the two functions. As the cycle time increases, the required total number of formwork levels reduces, which in turn reduces the cost but increases the time of RC work.

The study was then extended to compare the shore loads for different shore spacing and shore removal patterns. The simplified method assumes the shores as rigid. 2D building models were prepared in SAP2000 commercial software to compare the load on rigid and flexible shores for different spacing. It was found that the simplified method overestimates the average loads on the shores by 12–16%, but the locations of the levels of shores with a maximum load remain the same in both the cases. Further, the increase in the shore loads during removal was studied using 3D building models with different shore removal patterns. Row-wise removal of the shores was found to be the safest way. The most loaded row of the shores should be removed first as it results in a lesser increase in the remaining shore loads and thus ensures the safety of the structure.

The study contributes in the form of models to (1) guide a decision-maker in arriving at an informed decision for the selection of shores for a multi-storey building rather than relying on intuition alone; (2) decide the number of levels of shores-reshores to maintain safety during construction; (3) optimize the time and cost of RC work by maintaining safety during construction; and (4) understand the shore removal pattern without exceeding the capacity of the shores.

The proposed approach can significantly help designers, builders, practitioners, and decision-makers (1) to select the proper shores, (2) to find an adequate number of levels of shores-reshores to optimize the time and cost of RC work, and (3) to provide guidance on the removal of shores by maintaining the safety of the multi-storey building during construction.

Keywords: Single-leg Shores; Multi-leg Shores; Formwork; Number of Levels of Shores and Reshores; Optimization of Time; Optimization of Cost; Shore Removal; Multi-storey Building; Principal Component Analysis; Analytical Hierarchy Process; Genetic Algorithm; SAP2000.

सार

बहुमंजिला भवन निर्माण तेज गति से आगे बढ़ रहा है। एक निर्माता की प्रवृत्ति कम से कम संभव समय और कम से कम संभव लागत में निर्माण पूरा करने की है। फॉर्मवर्क, प्रबलित कंक्रीट (आरसी) निर्माण का एक महत्वपूर्ण घटक होने के नाते, बहु-मंजिला आरसी भवन के निर्माण में एक महत्वपूर्ण भूमिका निभाता है। क्षेत्रीय फॉर्मवर्क हालत के आधार पर शीथिंग मेंबर, जॉइस्ट, स्ट्रिंगर और एकल-पैर टेक या बहु-पैर टेक जैसे घटकों का निर्माण करता है।

निर्माण के दौरान संरचना की सुरक्षा भार स्थानांतरण तंत्र पर स्लैब से टेक तक निर्भर करती है, जिससे ये घटक क्षेत्रीय फॉर्मवर्क प्रणाली में महत्वपूर्ण हो जाते हैं। निर्माण के दौरान संरचना की सुरक्षा सुनिश्चित करने के लिए तटों के चयन पर सावधानीपूर्वक विचार और प्रभावी उपयोग की आवश्यकता होती है। इस लक्ष्य को प्राप्त करने के लिए, छह अलग-अलग उद्देश्यों की पहचान की गई थी। ये हैं: (१) बहु-मंजिला भवन निर्माण में तटों के चयन के लिए कारकों का मूल्यांकन करना, (२) बहु-मंजिला आरसी भवन निर्माण में स्लैब और तटों-पुनर्वसन पर भार का विश्लेषण करना, (३) बहु-मंजिला इमारत में आरसी कार्य के समय का अनुकूलन करना, (४) बहु-मंजिला इमारत में आरसी कार्य की लागत का अनुकूलन करना, (५) निर्माण के दौरान सुरक्षा बनाए रखने के द्वारा बहु-मंजिला इमारत में आरसी कार्य के समय और लागत का अनुकूलन करना, और (६) टेक रिक्ति और टेक हटाने पैटर्न के संबंध में टेक भार का मूल्यांकन करना। इन उद्देश्यों को प्राप्त करने के लिए विभिन्न विश्लेषण और मूल्यांकन उपकरण जैसे कि प्रमुख घटक विश्लेषण (पीसीए), विश्लेषणात्मक पदानुक्रम प्रक्रिया (एएचपी), और आनुवंशिक एल्गोरिथ्म (जीए) का उपयोग किया गया था।

तटों के चयन के लिए, एकल-पैर तटों और बहु-पैर तटों के लिए प्रासंगिक विशेषताओं पर विचार किया गया था। इन विशेषताओं को एक साहित्य समीक्षा और विशेषज्ञों के साथ चर्चा से संकलित किया गया

था। इसके परिणामस्वरूप एकल-पैर तटों के लिए कुल १४ विशेषताएं थीं, जबकि बहु-पैर तटों के चयन के लिए २१ विशेषताओं का संकलन किया गया था। प्रमुख घटक विश्लेषण (पीसीए) के आवेदन ने एकल-पैर तटों के लिए १४ विशेषताओं में से पांच कारकों को और बहु-पैर तटों के चयन के लिए २१ विशेषताओं में से सात कारकों को निकाला है। एकल-पैर तटों के चयन के पांच कारक थे: (१) टेक की विशेषताओं, (२) टेक लगाने में सुविधा, (३) टेक की लागत, (४) आवश्यक मात्रा में टेक की उपलब्धता, और (५) टेक की पुनः प्रयोज्य। बहु-पैर तटों के चयन के सात कारक थे: (१) टॉवर टेक की विशेषताएँ, (२) टॉवर टेक की आंतरिक विशेषताएँ, (३) आवश्यक मात्रा में टॉवर टेक की उपलब्धता, (४) टेक लगाने की आसानी, (५) टेक कनेक्शन और स्थापना उपकरण, (६) टेक की लागत, और (७) टेक की पुनः प्रयोज्य। इन कारकों का विश्लेषण विश्लेषणात्मक पदानुक्रम प्रक्रिया (एएचपी) का उपयोग करके उनकी सापेक्ष श्रेणी के लिए किया गया था। उपलब्ध विकल्पों में से तटों को चुनने में निर्णयकर्ता की मदद करने के लिए एक रूपरेखा आगे विकसित की गई थी।

एक परियोजना के लिए तटों की एक उचित प्रणाली के चयन के बाद, बहु-मंजिला इमारत के निर्माण के दौरान पटिया, तटों और पुनर्वसन के बीच भार वितरण के लिए विश्लेषण सुरक्षा के दृष्टिकोण से महत्वपूर्ण हो जाता है। इसके लिए, इस भार वितरण का अध्ययन करने के लिए सरलीकृत विधि (गुनडी और कबेला (१९६३ द्वारा विकसित)) पर विचार करते हुए एक अभिकलन कार्यक्रम विकसित किया गया था। विश्लेषण तीन अलग-अलग भौगोलिक स्थानों, अर्थात् भारत, अमेरिका और यूरोप के लिए किया गया है, क्योंकि ठोस शक्ति विकास के लिए उपयोग किए जाने वाले सूत्र यहां भिन्न हैं। यह देखा गया कि पटिया द्वारा प्राप्त समय के संबंध में पटिया द्वारा प्राप्त ताकत यूरोप के लिए सबसे अधिक थी, इसके बाद अमेरिका और उसके बाद भारत में सीमेंट के प्रकार, इलाज की विधि, और शक्ति गणना समीकरण के आधार पर। आरसी इमारतों के निर्माण अनुक्रम पर विचार करके एक ग्राफिकल यूजर इंटरफेस (जीयूआई) भी विकसित किया गया है, जो

विभिन्न मापदंडों जैसे कि तटों- संसाधन के स्तरों की संख्या, चक्र समय, अलग करने के समय को अलग करते हुए संरचना की सुरक्षा की तुलना करने में उपयोगकर्ताओं की मदद करता है। कंक्रीट का ग्रेड, आदि।

फॉर्मवर्क को जल्द से जल्द हटाने की आवश्यकता है क्योंकि यह निर्माण की कुल लागत का प्रमुख अनुपात लेता है और निर्माण के समय को प्राप्त करने में महत्वपूर्ण भूमिका निभाता है। इसलिए, पटिया और तटों के बीच भार वितरण के लिए विकसित कम्प्यूटेशनल कार्यक्रम आरसी कार्य के समय का अनुकूलन करने के लिए जीए के साथ संशोधित किया गया था। उद्देश्य समारोह समय और सुरक्षा मापदंडों पर विचार करके प्राप्त किया गया था। यह पाया गया कि न्यूनतम सुरक्षा आवश्यकताओं को बनाए रखते हुए शीघ्र निर्माण के लिए कंक्रीट के न्यूनतम एम-३० ग्रेड की आवश्यकता होती है। आरसी कार्य की लागत का अनुकूलन संरचना की सुरक्षा को बनाए रखते हुए एक बहु-मंजिला आरसी भवन में पटिया के निर्माण पर विचार किया गया था। उद्देश्य समारोह को तटों के स्तर की संख्या, पुनर्वसन के स्तर की संख्या, कंक्रीट के ग्रेड और ओवरहेड शुल्क के साथ विकसित किया गया था। कंक्रीट के निचले ग्रेड, जैसे कि एम-२० से एम-३०, तटों-रिसोर्स के स्तरों के कुछ संयोजनों के लिए सुरक्षा स्थिति का उल्लंघन करते हैं। यह इमारत की सुरक्षा को बनाए रखते हुए आरसी कार्य की लागत को कम करने के लिए तटों के स्तरों से अधिक स्तरों का उपयोग करने का सुझाव दिया गया था। इसके अलावा, आरसी कार्य के समय और लागत को एक साथ अनुकूलित किया गया था। समय और लागत के पहले व्युत्पन्न कार्यों को प्राथमिक दृष्टिकोण द्वारा एक साथ जोड़ा गया था, और दो कार्यों को अलग-अलग प्राथमिकता भार प्रदान करके अनुकूलन किया गया था। जैसे-जैसे चक्र का समय बढ़ता है, फॉर्मवर्क के स्तर की आवश्यक कुल संख्या घट जाती है, जो बदले में लागत को कम करती है लेकिन आरसी के काम के समय को बढ़ाती है।

अध्ययन को फिर अलग-अलग टेक रिक्ति और टेक हटाने के पैटर्न के लिए टेक के भार की तुलना करने के लिए बढ़ाया गया था। सरलीकृत विधि तटों को कठोर मानती है। अलग-अलग रिक्ति के लिए कठोर और लचीले तटों पर भार की तुलना करने के लिए SAP २000 वाणिज्यिक सॉफ्टवेयर में २-डी इमारत मॉडल तैयार किए गए थे। यह पाया गया कि सरलीकृत विधि तटों पर औसत भार को १२-१६% तक कम कर देती है, लेकिन अधिकतम भार के साथ टेक के स्तरों के स्थान दोनों मामलों में समान रहते हैं। इसके अलावा, हटाने के दौरान टेक के भार में वृद्धि को अलग-अलग टेक हटाने के पैटर्न के साथ ३-डी बिल्टिंग मॉडल का उपयोग करके अध्ययन किया गया था। तटों के रो-वार को सबसे सुरक्षित तरीका पाया गया। तटों की सबसे भरी हुई पंक्ति को पहले हटा दिया जाना चाहिए क्योंकि इससे शेष टेक का भार कम होता है और इस प्रकार संरचना की सुरक्षा सुनिश्चित होती है।

अध्ययन मॉडल के रूप में योगदान देता है (१) अकेले अंतर्ज्ञान पर भरोसा करने के बजाय बहु-मंजिला इमारत के लिए तटों के चयन के लिए एक सूचित निर्णय पर पहुंचने में एक निर्णय-निर्माता का मार्गदर्शन करता है; (२) निर्माण के दौरान सुरक्षा बनाए रखने के लिए तटों-पुनर्वसन के स्तरों की संख्या तय करना; (३) निर्माण के दौरान सुरक्षा बनाए रखकर आरसी कार्य के समय और लागत का अनुकूलन करें; और (४) टेक की क्षमता को पार किए बिना टेक हटाने के पैटर्न को समझें।

प्रस्तावित दृष्टिकोण डिजाइनरों, बिल्डरों, चिकित्सकों और निर्णय लेने वालों (१) को समुचित तटों का चयन करने में मदद कर सकता है, (२) आरसी कार्य के समय और लागत का अनुकूलन करने के लिए तटों-पुनर्वसन के स्तर की पर्याप्त संख्या का पता लगाने के लिए, और (३) निर्माण के दौरान बहुमंजिला इमारत की सुरक्षा को बनाए रखते हुए तटों को हटाने पर मार्गदर्शन प्रदान करना।

कुंजी शब्द: एकल-पैर टेक; बहु-पैर टेक; शटरिंग निर्माण; तटों और रेज़र के स्तरों की संख्या; समय का अनुकूलन; लागत का अनुकूलन; शोर निकालना; बहुमंजिला इमारत; प्रमुख घटक विश्लेषण; विश्लेषणात्मक पदानुक्रम प्रक्रिया; आनुवांशिक प्रमेय; SAP २०००

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LIST OF ABBREVIATIONS

ACI	American Concrete Institute
ACO	Ant colony optimization
AHP	Analytical hierarchy process
ANN	Artificial Neural Network
ASTM	American Society for Testing and Materials
BDT	Boosted decision tree
CI	Consistency Index
CR	Consistency Ratio
D	Self-weight of the concrete slab
DSR	Delhi schedule of rates
DT	Decision tree
f_{ck}	Characteristic strength of concrete
FoS	Factor of Safety
GA	Genetic algorithm
GUI	Graphical User Interface
MATLAB	Matrix Laboratory
MAWA	Modified adaptive weight approach
ML	Multi-leg shores
ms	Installation time
MSP	Microsoft project
n	Number of storey
NDT	Non-destructive testing

NN	Neural network
<i>nr</i>	Number of levels of reshores
NR	Normal and repid hardening cement
<i>ns</i>	Number of levels of shores
OC	Overhead charges
PC	Penalty cost
PCA	Principal Component analysis
PNN	Probabilistic neural network
PV	Penalty value
RC	Reinforced concrete
RS	Rapid hardening high strength cement
SAP2000	Structural Analysis Program
SAPV2	Structural Analysis Program Version 2
SH	Slow hardening cement
SL	Single-leg shores
SLD	Safety Level Difference
SPSS	Statistical package for the social sciences
<i>T</i>	Cycle time
TCT	Time cost trade-off
<i>t_s</i>	Stripping time