Analysis of different phased construction models for two-tube tunnels on motorways

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Summary

This paper presents the analysis of different phased construction models for two-tube tunnels on motorways.
Namely, last fifteen years showed very intense motorway construction in Croatia, and construction of tunnels as well, as their key elements.
Since there are several motorway concessionaires in Croatia, different construction models and models of construction progress have been introduced, with great impact on tunnels. Some concessionaires built motorways in full profile, others introduced phased construction. Significant differences appeared during tunnel construction, depending on tunnel length, thus creating the following four main phased construction models for two-tube tunnels:
HAC as Investor, built the A1 motorway (Split-Zagreb) in its full profile, as well as almost all tunnels on it.
Only exception to this were long tunnels (Tunnels “Mala Kapela” and “Sveti Rok” – both longer than 5000 m). These were built in two phases, although the motorway was built in its full profile.
ARZ as the Investor built the A6 motorway (Bosiljevo–Rijeka) in two phases as well as all tunnels on it.
AZM as Investor, built the A2 motorway in its full profile, except 3,7 km long section where the “Sveta Tri Kralja” tunnel is located, which is going to be built in two phases.

The only common factor to all concessionaires in Croatia is that all tunnels on Croatian motorways were built as two-tube tunnels for unidirectional traffic. Only difference are the phased construction models used, the total costs and construction progress, as well as some technological and safety factors.

Keywords:phase construction, tunnel

1. Introduction

This paper presents a comparative analysis of all four phased construction models for two-tube tunnels, using information gained during construction of different tunnels on Croatian motorways. They all have the same cross-section, all were built using the “drill & blast technique”, all are based on the NATM and all were in similar rock conditions.

Main comparative parameters, to be used in the comparative analysis are: costs, safety, traffic volume, technology, regulations, risks, construction progress...

The paper aims to find the optimal construction model for two-tube tunnels on motorways, from the aspects of above mentioned comparative parameters.

This paper is a brief abstract from an authors extensive research which is related to this subject and as such is published in authors postgraduate masters theses at Faculty of Civil engineering at University of Zagreb, Croatia [1]. Numerical values and calculation results presented in this paper were taken from above mentioned postgraduate masters theses.

2. Comparative analysis of phased construction models

2.1. Model A - simultaneous construction of both tunnel tubes

This construction model can not be called an actual phased construction model, because the both tunnel tubes are excavated and built simultaneously, and opened for traffic at the same time in full motorway profile.
In cases of secured financial resources and sufficient traffic volume this is the best phased construction model (the cheapest and the safest) for two-tube tunnels on motorways, for several reasons:

- simultaneous construction and opening for traffic of both tunnel tubes results with earlier ending of all works and with earlier start of exploitation of the tunnel as an investment,
- there are no additional costs due to subsequent construction of the second tunnel tube as in other phased construction models,
- simultaneous construction of both tunnel tubes provides the maximum possible construction progress, respectively the maximum possible technique and technology effect compared to other phased construction models,
- thereby, construction costs are as low as possible, compared to other phased construction models, for following reasons:
  - construction costs of a tunnel are decreasing as the tunnel excavation progress speeds up,
  - as a result of the maximum possible efficiency of contractors resources,
  - indirect construction costs are significantly smaller compared to other phased construction models, especially the costs of preliminary works,
  - there are no restrictions in work progress, as to the other phased construction models,
  - distance between tunnel tube axes need not be increased (from min. 25 m), since tunnel construction does not effect motorway horizontal elements.

Based on these reasons, the previously mentioned postgraduate masters theses concludes that „in cases where tunnel excavation of both tunnel tubes is simultaneous, excavation unit prices are about 10 % lower than in cases where only one tunnel tube is being excavated“[1].

Besides the above shown financial and technological indicators, traffic, safety and regulatory conditions must also be considered, which are all in favor of this phased construction model, because:

- implementation of this phased construction model provides maximum traffic safety and traffic flow, as appropriate for full motorway profile, since the traffic is unidirectional in each tunnel tube,
- optimal ventilation, evacuation, intervention and traffic safety systems are achieved, according to all competent regulations and guidelines [2]. In this phased construction model longitudinal ventilation is being used, as the most economic system for tunnel ventilation.

2.2. Model B - construction of one tunnel tube in the first phase, and the second tunnel tube after a certain time distance

In this phased construction model only one tunnel tube is being built and opened for bidirectional traffic in the first phase, while the other tunnel tube will be excavated and built after a certain time distance along with traffic flow in the first tube. After finishing second tunnel tube traffic in now two-tube tunnel gets unidirectional in each tunnel tube.

This phased construction model applies in cases with insufficient funds and/or less traffic volume, and basic charateristics for comparison with other phased construction models are:

- with phased construction of two-tube tunnel completion of all works on both tubes gets significantly delayed and exploitation of a tunnel as an investment in its full-scale is postponed,
- time distance between construction phases can cause a considerable difference in costs for key resources used in the construction of first tunnel tube, as compared to construction of the second tunnel tube, which results in a significant difference in total costs for different

construction phases,

- indirect construction costs are almost twice as big as in other phased construction models, mostly because the preliminary works are being carried out twice and because the work progress on tunnel excavation lasts much longer, caused by restrictions,
- in this phased construction model certain actions must be performed twice, causing additional costs:
  - drafting of project documentaton (drawings and blueprints) and project control (revision),
  - administrative proceedings,
  - public tender proceedures for design, construction, equipment supply and supervision,
  - construction site establishment of contractor and project management,
- phased construction of a two-tube tunnel with time distance alongside with traffic flow in the first tunnel tube during the excavation works in the second tunnel tube results with the minmum possible work progress, as a result of the minimum possible contractors resources efficiency (very low technique and technology effect), mostly because:
  - there are significant restrictions in excavation of a second tunnel tube because of the blasting impact on first tunnel tube through which traffic flows (excavation progress is 2 to 3 times slower than the one achieved in the first tunnel tube),
  - certain increase of excavation progress is possible with the increase in bearing capacity of the first tunnel tube, which is possible with more steel reinforcement is used, and this increases overall construction costs,
  - beside above mentioned restrictions, existence of only 2 excavation faces also results in very low efficiency of contractor's resources (maximum up to 50%),
  - distance between tunnel tube axes must be increased (from min. 25 m), thus the tunnel construction influences the motorway horizontal elements,

Based on above listed charateristics, the already mentioned postgraduate masters theses concludes that in case of phased construction model of a two-tube tunnel with a time distance between the two construction phases „excavation costs of a second tunnel tube increases for about 30 %, because of different restrictions during it's construction [1].

Besides the above shown financial and technological indicators, traffic, safety and regulatory conditions must also be considered:

- traffic conditions are variable, depending on the construction phase,
- during the periods of blasting in the second tunnel tube closing the traffic in the first tunnel tube is necessary,
- bidirectional traffic flow in first tunnel tube requires much more traffic signs and signalization, tunnel equipment as well as some additional construction measures,
- in this phased construction model the minimum safety demands regarding the tunnel vantilation, evacuation, intervention and traffic safety defined by respective regulations and guidelines [2] are not acomplished. It is because of usage of longitudinal ventilation in one tunnel tube with bidirectional traffic and because of the lack of emergency exits, regardless of tunnel length,
- a disadvantage of this phased construction model is bidirectional traffic in one tunnel tube, which has a much lower traffic safety level,

This phased construction model was implemented in the 90-ies, before some large scale accidents in European tunnels and before implementation of new EU regulations regarding safety in tunnels. It was justified with rationalization of costs, insufficient traffic volume and as a temporary solution.

2.3. Model C - construction of one tunnel tube and service tunnel in the first phase, and the other tunnel tube after a certain time distance

Phased construction model C is in fact a modified phased construction model B, which is harmonised with valid regulations and guidelines [2] so that satisfactory safety standards regarding ventilation i emergency evacuation can be achieved.

In this phased construction model one tunnel tube for bidirectional traffic with transversal or semi-transversal ventilation system and service tunnel with cross-connections to the main tube are being built simultaineously in first phase, while the other tunnel tube will be excavated and built after certain time distance, along with traffic flow in the first tube.
This phased construction model has two alternatives, depending on final function of service tunnel after completion of all works:

- alternative 1 – extension and upgrading of a service tunnel to the full tunnel tube profile in the second phase, where it becomes a second tunnel tube (approx. 15% less excavation volume compared to alternative 2)
- alternative 2 – excavation of new tunnel tube in second phase, where service tunnel partly looses it's function (approx. 15% more excavation volume and primary support)

This phased construction model applies in cases with lack of finance and/or less traffic volume, but unlike previous model (model B), with implementation of this model satisfactory safety requirments are reached, but wit much bigger total construction costs.

The basic charateristics for comparison with other phased construction models are very similar to the previous model, regardless of alternative used, namely: delay of completion of all works, post-poned full exploitation, difference in costs between construction phases, double indirect construc-tion costs, minimum possible work progress, very big construction costs, significant restrictions in excavation because of the mine blasting impact, enlargement of tunnel tubes axis distance.

As in the previous phased construction model, regardless of alternative used, we can also say that in case of phased construction model of a two-tube tunnel with time distance between construction phases „excavation costs of a second tunnel tube increases for about 30 % [1].

Due to the requirement that the first tunnel tube must have transversal or semi-transversal ventila-tion system, certain additional construction works are necessary compared to tunnel tubes with longitudinal ventilation:
Tunnel tube with semi-transversal ventilation:

- cross section of tunnel tube and excavation volume are bigger for approx. 14%,
- increasing of primary support for approx. 15%,
- increasing of concrete work on secondary tunnel lining for approx. 16,5%,
- increasing of waterproofing for approx. 15%,

Tunnel tube with transversal ventilation:

- cross section of tunnel tube and excavation volume are bigger for approx. 22%,
- increasing of primary support for approx. 25%,
- increasing of concrete work on secondary tunnel lining for approx. 25%,
- increasing of waterproofing for approx. 20%

Besides additional works caused by enlargement of cross section of tunnel tube, both ventilation systems require construction of an additional sealing, which divides traffic profile from air canals, as well as fire protection of a tunnel construction. It is obvious that transversal or semi-transversal ventilation systems in large scale expand total costs for construction of a tunnel.
Second tunnel tube can have longitudinal ventilation system, or the same system as in the first tunnel tube.

Besides the above shown financial and technological indicators, traffic, safety and regulatory conditions must also be considered for this phased construction model:

- regarding the traffic conditions this phased construction model is somewhat better than the previous one (model B), but because of the bidirectional traffic in one tunnel tube while the other tunnel tube is being excavated, this phased construction model is still not the best solution,
- regarding the safety measures this phased construction model fulfils ventilation, intervention, evacuation and traffic safety requirements, therefore it is better than the previous one (model B),

Considering the total construction costs, this phased construction model is the most expensive (generating the biggest costs), especially compared to first analyzed model (model A). Main reasons for that are:

- 30% bigger excavation costs in second phase because of restrictions in blasting,
- 10% bigger excavation costs in second phase because of very low resources efficiency,
- 15% bigger excavation costs in case of implementation of alternative 2,
- 15% bigger costs of primary support because of the excavation of service tunnel,
- 25%-40% bigger total construction costs in first phase (or in both) because of the implementation of transversal or semi-transversal ventilation systems,
- double costs of actions which must be performed twice and indirect construction costs (2,3% + till max. 12%)

2.4. Model D – simultaneous excavation of both and complete construction of only one tunnel tube in the first phase, and completion of second tunnel tube after a certain time distance

Phased construction model D is in fact a modified phased construction model A, wehere the model A is divided into two phases. In the first construction phase both tunnel tubes and their cross-connections are being excavated simultaneously and only one of tunnel tubes is being completed and opened for bidirectional traffic, while the other tunnel tube stays excavated and supported for the purpose as service tunnel.
In the second construction phase, after certain time period (when traffic volume increases 10 000 vehicles/lane), second tunnel tube is completed without disturbance, along with undisturbed traffic flow in the first tunnel tube.
This solution is compromise between traffic demands and safety of tunnel users in the first construction phase, and cost-effectiveness of construction of a two-tube tunnel in total.

This phased construction model has been implemented during construction of two longest tunnels on Croatian motorways; the Mala Kapela Tunnel (5780 m) and Sveti Rok Tunnel (5679 m).

This phased construction model applies in cases with lack of finance and/or less traffic volume, but unlike previous two phase construction models (models B and C) with implementation of this phased construction model satisfactory tunnel safety for users is achieved with much smaller total construction costs, compared to two above mentioned phased construction models.

Main charateristics for comparison with other phased construction models are:

- much lesser financial impact of time distance between construction phases,
- earlier completion of all works and start of exploitation of a tunnel as an investment than in previous two phased construction models (models B and C), because second construction phase lasts much shorter,
- here as well exists double costs of actions which must be performed twice,
- indirect construction costs are approx. 50% bigger than to phased construction model A and 50% smaller than to phased construction models B and C,
- this phased construction model requires additional costs regarding the construction site safety measures during long term work suspension and conservation of construction site,
- basic technological parameters are almost the same to the ones in phased construction model A,

Because of all that in this phased construction model maximum possible construction progress is achieved, respectively the maximum possible technique and technology effect, almost the same to the phased construction model A, opposite to phased construction models B and C.

Traffic charateristics of this phased construction model are unfavourable compared to the phased construction model A, but they are more favourable than to previous two phased construction models (modeli B i C), for next several reasons:

- there are no traffic restrictions in first tunnel tube during the second construction phase,
- second construction phase lasts much shorter than to the other phased construction models, what results in much faster activation of both tunnel tubes for unidirectional traffic.

This phased construction model doesn't reduce tunnel users safety in the first construction phase, while is bidirectional traffic with relativly low traffic volume, compared to previous phased construction model (model C), and it is compliant with all competent tunneling regulations and guidelines.

3. Conclusions

For quality conclusion about optimal phased construction model for two-tube tunnels on motorway it is advisable to make a brief tabular view of compared construction costs for all phased construction models presented in this paper with all their possible alternatives and sub-alternatives.

For determining the share of certain group of construction works in total construction costs of a tunnel, data from contractual bill of quantities for 6 two-tube tunnels on motorway A1, who are now being built in similar rock conditions and have the same cross-section, was analyzed.

Phased construction model A will be a reference model for comparison of tunnel construction costs (with index 100) and all other phased construction models will be compared with it.

The attached Table (Fig. 1) clearly shows construction costs of all phased construction models and sub-models (in total 11 possible alternatives), and it can be used for ranking of phased construction models by construction costs:

1. model A – lowest construction costs, as expected,
2. model D – total construction costs are higher by approx. 5% compared to model A, making it very acceptable phased construction model,
3. model B – total construction costs are higher by approx. 17 % compared to model A, and by approx. 12% compared to model D, which is still acceptable, if only construction costs are taken into account,
4. model C – highest total construction costs; depending on alternative total construction costs range from approx. 34% to approx. 70% higher than construction costs for model A.

Taking into account all other mentioned criteria (financial, technologic, traffic, safety, regulatory) it is obvious that phased construction model A is the best model by all criteria, what is logical.

On the other hand, according to all other criteria, except construction costs, phased construction model B is the worst phased construction model, moreover by the safety and regulatory criteria it is not acceptable as phased construction model for two-tube tunnels on motorways.

Phased construction model C is satisfactory by all criteria except the probbably most important one - total construction costs, what makes it the most expensive phased construction model and thus unacceptable.

As optimal phased construction model appears to be model D, which is by all criteria (costs, traffic, safety, regulatory) second by ranking.
Basic charateristics of this phased construction model is that it satisfies all defined criteria, and it is not much more expensive than the best solution–phased construction model A.

In cases with lack of finance and/or less traffic volume, the best phased construction model for two-tube tunnels on motorway is phased construction model D, where the satisfactory optimisation of costs and safety is achieved.

CONSTRUCTION COSTS COMPARISON

	MODEL A COMPLETE CONSTRUCTION	MODEL B PHASE CONSTRUCTION	MODEL C PHASE CONSTRUCTION								MODEL D PHASE CONSTRUCTION
FIRST PHASE	SIMULTANEOUS CONSTR. OF BOTH TUNNEL TUBES	CONSTRUCTION OF ONLY ONE TUNNEL TUBE	CONSTRUCTION OF ONE TUNNEL TUBE AND SERVICE TUNNEL				CONSTRUCTION OF ONE TUNNEL TUBE AND SERVICE TUNNEL				EXCAVATION OF BOTH TUNNEL TUBES COMPLETION OF ONLY ONE TUNNEL TUBE
VENTILATION SYSTEM	LONGITUDINAL VENT.	LONGITUDINAL VENT.	SEMI-TRANSVERSAL VENTILATION				TRANSVERSAL VENTILATION				LONGITUDINAL VENT.
DESIGN AND REVISION	2,04	3,06	3,06	3,06	3,06	3,06	3,06	3,06	3,06	3,06	2,55
CONSTRUCTION WORKS											
PRELIMINARY WORKS	7,00	7,00	7,00	7,00	7,00	7,00	7,00	7,00	7,00	7,00	7,00
TUNNEL EXCAVATION	30,07	16,54	17,14	17,14	17,14	17,14	18,34	18,34	18,34	18,34	30,07
PRIMARY SUPPORT	11,43	5,72	6,57	6,57	6,57	6,57	7,14	7,14	7,14	7,14	11,43
CONCRETE WORKS AND PORTALS	26,95	13,48	15,70	15,70	15,70	15,70	16,84	16,84	16,84	16,84	13,48
WATERPROOFING AND DRAINAGE	8,86	4,43	5,09	5,09	5,09	5,09	5,32	5,32	5,32	5,32	4,43
PAVEMENT STRUCTURE	2,82	1,41	1,41	1,41	1,41	1,41	1,41	1,41	1,41	1,41	1,41
PRE-CUT DESIGN	1,44	0,72	0,72	0,72	0,72	0,72	0,72	0,72	0,72	0,72	0,72
CONSTRUCTION WORKS TOTAL	88,57	49,29	53,64	53,64	53,64	53,64	56,78	56,78	56,78	56,78	68,54
ADDITIONAL WORKS											
SEALING	.....	.....	10,00	10,00	10,00	10,00	12,00	12,00	12,00	12,00	.....
SERVICE TUNNEL	.....	.....	6,23	6,23	6,23	6,23	6,23	6,23	6,23	6,23	.....
ADDITIONAL WORKS TOTAL	.....	.....	16,23	16,23	16,23	16,23	18,23	18,23	18,23	18,23	.....
EQUIPMENT											
TUNNEL INSTALLATION	7,26	4,36	4,36	4,36	4,36	4,36	4,36	4,36	4,36	4,36	4,36
VENTILATION	2,13	1,07	1,47	1,47	1,47	1,47	1,64	1,64	1,64	1,64	1,07
EQUIPMENT TOTAL	9,39	5,42	5,83	5,83	5,83	5,83	6,00	6,00	6,00	6,00	5,42
FIRST PHASE TOTAL	**100,00**	**57,77**	**78,75**	**78,75**	**78,75**	**78,75**	**84,06**	**84,06**	**84,06**	**84,06**	**76,51**
SECOND PHASE	.....	CONSTRUCTION OF SECOND TUNNEL TUBE	**ALTERNATIVE 1** - EXTENSION AND UPGRADING OF SERVICE TUNNEL		**ALTERNATIVE 2** - CONSTRUCTION OF NEW TUNNEL TUBE		**ALTERNATIVE 1 - EXTENSION AND UPGRADING** OF SERVICE TUNNEL		**ALTERNATIVE 2 - CONSTRUCTION OF** NEW TUNNEL TUBE		COMPLETION OF SECOND TUNNEL TUBE
VENTILATION SYSTEM	.....	LONGITUDINAL VENT.	SEMI-TRANS. VENT.	LONGITUDINAL VENT.	SEMI-TRANS. VENT.	LONGITUDINAL VENT.	TRANSVERSAL VENT.	LONGITUDINAL VENT.	TRANSVERSAL VENT.	LONGITUDINAL VENT.	LONGITUDINAL VENT.
DESIGN AND REVISION	.....	1,02	1,02	1,02	1,02	1,02	1,02	1,02	1,02	1,02	0,51
CONSTRUCTION WORKS											
PRELIMINARY WORKS	.....	7,00	7,00	7,00	7,00	7,00	7,00	7,00	7,00	7,00	3,50
TUNNEL EXCAVATION	.....	21,50	17,16	15,05	24,51	21,50	18,36	15,05	26,23	21,50	.....
PRIMARY SUPPORT	.....	5,72	6,57	5,72	6,57	5,72	7,14	5,72	7,14	5,72	.....
CONCRETE WORKS AND PORTALS	.....	13,48	15,70	13,48	15,70	13,48	16,84	13,48	16,84	13,48	13,48
WATERPROOFING AND DRAINAGE	.....	4,43	5,09	4,43	5,09	4,43	5,32	4,43	5,32	4,43	4,43
PAVEMENT STRUCTURE	.....	1,41	1,41	1,41	1,41	1,41	1,41	1,41	1,41	1,41	1,41
PRE-CUT DESIGN	.....	0,72	0,72	0,72	0,72	0,72	0,72	0,72	0,72	0,72	0,72
CONSTRUCTION WORKS TOTAL	.....	54,25	53,65	47,80	61,01	54,25	56,79	47,80	64,66	54,25	23,54
ADDITIONAL WORKS											
SEALING	.....	.....	10,00	.....	10,00	.....	12,00	.....	12,00	.....	.....
RADOVI ZBOG RAZMICANJA OSI	.....	1,60	1,60	1,60	3,20	3,20	1,60	1,60	3,20	3,20	.....
ADDITIONAL WORKS TOTAL	.....	1,60	11,60	1,60	13,20	3,20	13,60	1,60	15,20	3,20	.....
EQUIPMENT											
TUNNEL INSTALLATION	.....	3,27	3,27	3,27	3,27	3,27	3,27	3,27	3,27	3,27	3,27
VENTILATION	.....	1,07	1,47	1,07	1,47	1,07	1,64	1,07	1,64	1,07	1,07
EQUIPMENT TOTAL	.....	4,33	4,74	4,33	4,74	4,33	4,91	4,33	4,91	4,33	4,33
SECOND PHASE TOTAL	.....	**59,60**	**71,01**	**54,75**	**79,96**	**62,80**	**76,32**	**54,75**	**85,79**	**62,80**	**28,38**
TOTAL CONSTRUCTION COSTS	**100,00**	**117,37**	**149,75**	**133,50**	**158,71**	**141,55**	**160,38**	**138,81**	**169,85**	**146,86**	**104,88**

Fig. 1 Comparison of construction costs for all phased construction models for two-tube tunnels

4. References

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