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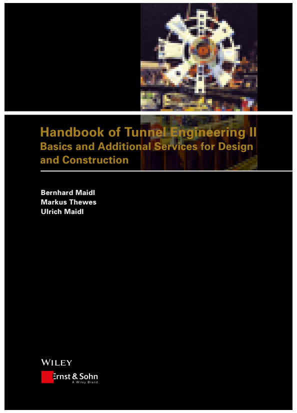
Bernhard Maidl, Markus Thewes, Ulrich Maidl

Handbook of Tunnel Engineering II

Basics and Additional Services for Design and Construction

- **Valuable assistance in the planning and execution of tunnels**
- **internationally known authors**
- **complements Vol. 1complements Vol. 1**

The book deals with almost all aspects of annular gap lubrication in pipe jacking – from ground conditions, through the properties of bentonite to the technical aspects. There is also a collection of calculations and suggested values for bentonite consumption quantities.



2014 · 458 pages · 261 figures · 79 tables

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ABOUT THE BOOK

Pipe jacking is a construction process for the no-dig laying of pipes. Successful pipe jacking demands low skin friction between the ground and the jacked pipe. This is achieved with bentonite lubrication. The bentonite slurry fed into the annular gap fulfils several purposes. It stabilises the annular gap by supporting the surrounding ground and reduces friction contact between ground and jacked pipe. The Bentonite Handbook deals comprehensibly with the relevant aspects of annular gap lubrication: starting with the ground conditions, which are of decisive importance for lubrication, through the rheological properties of the bentonite slurry to the technical components of lubrication technology and lubrication strategy. The use of standardised measuring apparatus is described as well as mixing equipment and the automatic lubrication system. Overview tables with calculations and suggested values for bentonite consumption quantities depending on the prevailing ground conditions and the pipe jacking parameters complete the recommendations.

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Foreword to the English edition

The “black book of tunnelling” has become a standard work in German-speaking countries since its first German edition in 1984. It can be found on every tunnel site and in every design office – whether contractor or consultant. Students at universities and technical colleges use it as a textbook.

For many years, colleagues from abroad have been asking me for an English edition. Now the time has come to publish the two-volume book in English. An important step was that the publisher of the first German edition, VGE, gave their permission for the publishing of the English edition by Ernst & Sohn, Berlin. Special thanks are due to Dr. *Richter* from Ernst & Sohn for his successful negotiations. However, preparation of the text for the translation showed that the 3rd German edition required updating and extending. In particular, the standards and recommendations have been revised. This will all be included in a 4th German edition, which will be published soon. Changes to the standards and recommendations are given in this edition, with the references stating the latest version.

As with all books, the English edition has also required the collaboration of colleagues. Professor Dr.-Ing. *Markus Thewes*, who has succeeded me as the holder of my former university chair, and my son Dr.-Ing. *Ulrich Maidl*, managing director of the consultant MTC, have joined me in the team of authors. Dipl.-Ing. *Michael Griese* from MTC is the overall coordinator, assisted by Dipl.-Ing. *Stefan Hintz* from MTC. I thank all those involved, also the translator *David Sturge* and the employees of the publisher Ernst & Sohn in Berlin.

Bochum, in September 2013 *Bernhard Maidl*

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*) The titles of some chapters have changed since their initial announcement in Handbook of Tunnel Engineering, Vol I, with no effect to the content itself.

1 General Principles for the Design of the Cross-section

1.1 General

The shape and size of the design cross-section derive firstly from the purpose of the tunnel (rail tunnel, road tunnel, sewer, water tunnel or pressure tunnel for a hydropower station) and thus the required clearance gauge. Secondly, the dimensions will also be influenced, as is the alignment, by the geotechnical or structural conditions in the ground to be passed through; whether earth or water pressure could occur or whether no external loading is to be expected. Thirdly, the construction process also has an effect on the design of the cross-section; for a given clearance gauge, the most economic cross-section is that which can be constructed with the least excavation and support technology and with the optimal machinery, taking into account the given basic shape.

1.2 Dependence on intended use

1.2.1 Road tunnels

General. The traffic conditions in a road tunnel should in principle correspond to those in the open air. Road tunnels are, however, special sections of a road and demand stringent requirements for their construction, maintenance and operation. Road tunnels have to meet particular requirements regarding road safety and operational safety. When the needs of traffic management are balanced against economy, it is therefore necessary and justifiable in many cases to limit the speed compared to parts of the road in the open air. The permitted maximum speed is thus normally limited to 80 km/h in road tunnels, which inevitably differentiates the traffic flow in tunnels from roads in the open air.

Tunnel cross-section. Road tunnels with two-way traffic and those with one-way traffic are fundamentally different. Two-way tunnels normally consist of a single tube with one lane in each direction. In one-way tunnels, the traffic in each direction is constructionally separated, for example through the provision of two bores. While in the past each bore was often laid out with two lanes without a hard shoulder, the changing composition of the traffic and ever increasing traffic loading will also demand three lanes without hard shoulder, and in exceptional cases even three lanes with a hard shoulder.

The design of the cross-section of road tunnels has to consider road traffic aspects, operational equipment and the tunnel structure. The design of the cross-section of a cut-and-cover road tunnel is often subject to different constraints from a mined underground tunnel. Some examples of cross-sections of mined road tunnels are shown in Fig. 1-1.

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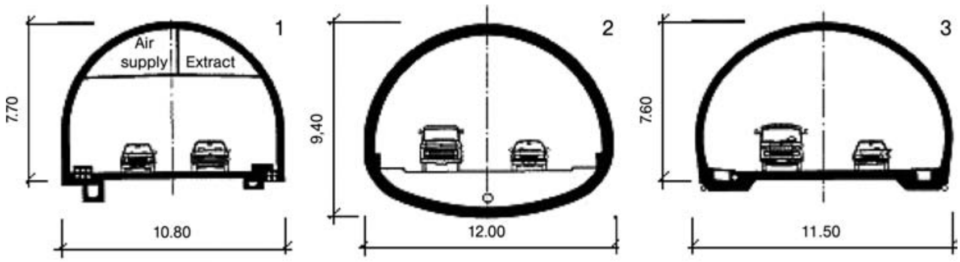

1 Gotthard Tunnel, Switzerland 1969 to 1980
2 Westtangente, Bochum 1980 to 1981
3 Rennsteig Tunnel, Thuringia 1998 to 2003

Figure 1-1 Cross-sections of some mined road tunnels.

The starting point of all considerations does, of course, remain the space required for the road intended to run through the tunnel. The required total cross-section can often be twice that of the actual cross-section for traffic, and the cross-sectional area at breakdown bays of autobahn tunnels can be up to 200 m^2 and more. The space required is also influenced by the horizontal and vertical alignments selected for the project.

The design of tunnel cross-sections in Germany is based on the guidelines for the equipment and operation of road tunnels (RABT) [77], also taking into account the guidelines for road design; cross-sections (RAS-Q) [76] and alignment (RAS-L) [75]. These guidelines include requirements for the standard cross-section, the structure or vehicle gauge to be maintained, the transverse and longitudinal gradients in tunnels and the provision of breakdown bays and emergency exits.

Standard cross-section. The standard cross-section of a road tunnel has to provide dimensions to enable the installation of equipment like lighting, ventilation, traffic management and safety technology, normally outside the clearance gauge. Particularly ventilation and signage equipment may demand an enlargement of the tunnel cross-section. In order to limit the multitude of possible cross-sections – also for economic reasons – the standard cross-sections of roads in the open air are assigned to road cross-section types in tunnels. The selection of road tunnel cross-sections is carried out according to [33] (Fig. 1-2).

In tunnels intended for two-way traffic, the standard cross-section type 10,5 T with 7.50 m paved width between the kerbs is normally provided. This cross-section is also used in open-air sections where wider verges are provided due to high heavy goods traffic volumes. In the course of a road with 2 + 1 RQ 15,5 sections (two lanes with an overtaking lane), sections running through tunnels are also constructed to section 10,5 T. The overtaking lane in this case thus has to be terminated in good time before the tunnel. Special solutions like an additional crawler or climbing lanes in the tunnel are an exception. When in exceptional cases tunnel sections on main roads only provide RQ 9,5 section, cross-section 10,0 T should be used [33].

The normal layout in tunnels with multi-lane carriageways in one direction should be a reduced standard road section without hard shoulders (26 t or 33 t), although it is justifiable under certain economic or traffic conditions to provide hard shoulders. Economic aspects in this case could be the construction and operating costs resulting from the length of the tunnel or the costs resulting from congestion and accidents. The hard shoulders are available for vehicles to swerve to the side or stop in an emergency. They often allow continued multi-lane traffic flow after minor accidents or breakdowns and also simplify maintenance work without serious disruption of traffic flow. The width of hard shoulders varies depending on cross-section type (Fig. 1-2). It is

– for cross-section type 29,5 T 2.50 m.
– for cross-section types 26 T and 33 T 2.00 m.
– for cross-section type 26 Tr 1.50 m.

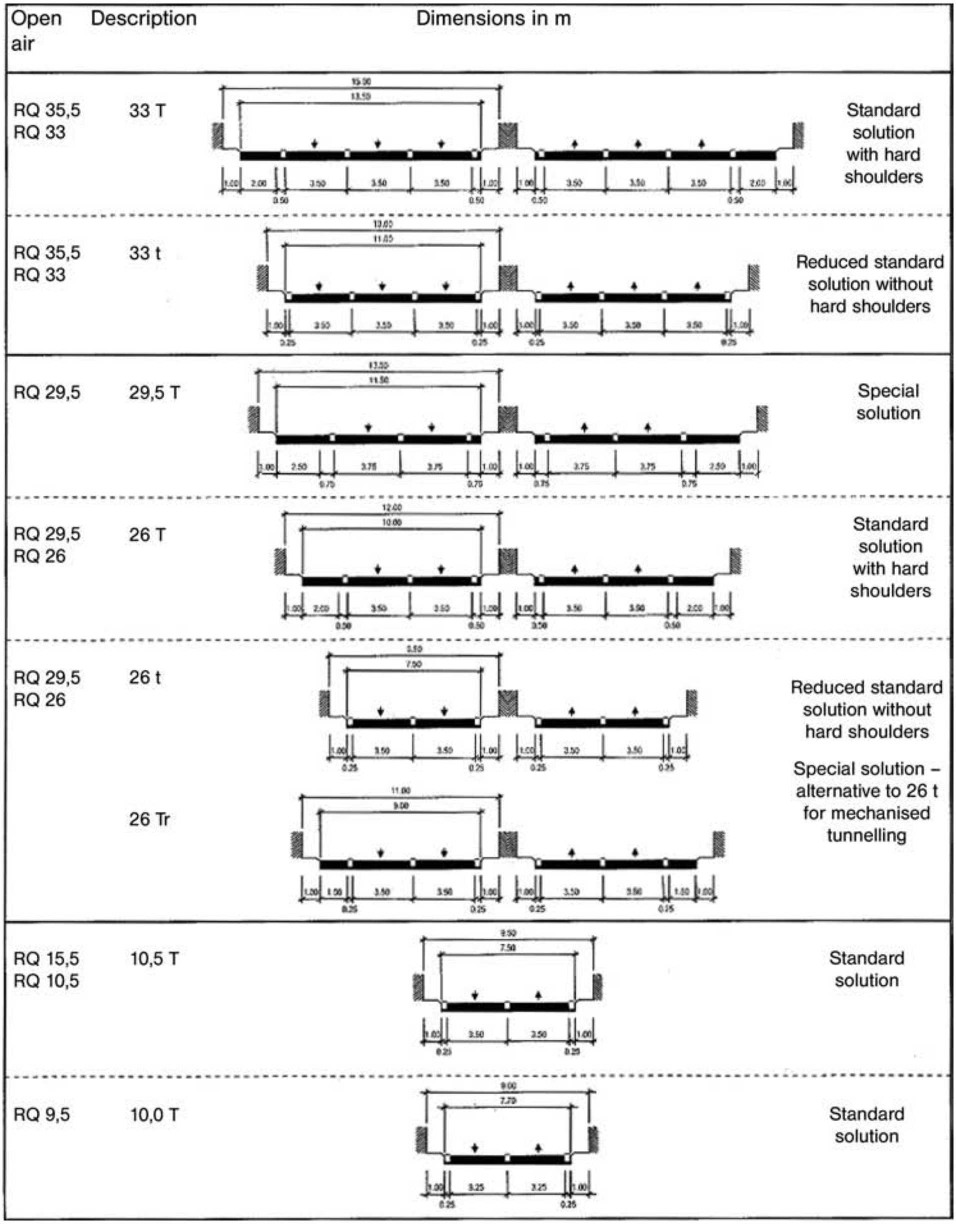

Figure 1-2 Standard cross-sections for road tunnels [33, 77].

For the layout of hard shoulders in tunnels, reference should be made to [33]. Using this decision-making process, it should be checked whether the additional utility resulting from a hard shoulder exceeds its extra cost. Using the diagrams for use with this process, it can be seen that the decision to provide the cross-sections with hard shoulders (26 T or 33 T) can only be justified under very favourable construction conditions or with a high volume of heavy good vehicle traffic combined with steep gradients. This process applies for multi-lane carriageways in one direction in road tunnel up to 2,000 m long.

The reduced form of special cross-section 26 Tr should only be considered for tunnels to be driven with shield machines. In this case, the reduced hard shoulder replaces the otherwise necessary breakdown bays along the entire length [33].

Cross-section type 29,5 T is only worth considering for very unusual cases and in any case only for very short tunnels with an exceptionally low-cost construction method.

Clearance gauge, traffic gauge. The clearance gauge denotes the space for the road cross-section, which has to be kept clear of obstructions. It consists of the traffic gauge and the safety margins at the top and the sides. The necessary cross-sectional area of the clearance gauge ensues from the traffic purpose of the tunnel. It is derived from the applicable standard cross-section in the open air; the permissible restriction of the cross-section inside structures also has to be considered (RAS-Q [76]).

The total width of the clearance gauge is the sum of the widths of the side safety margins, the carriageway, the verges and any additional lanes (for example hard shoulders) (Fig. 1-3).

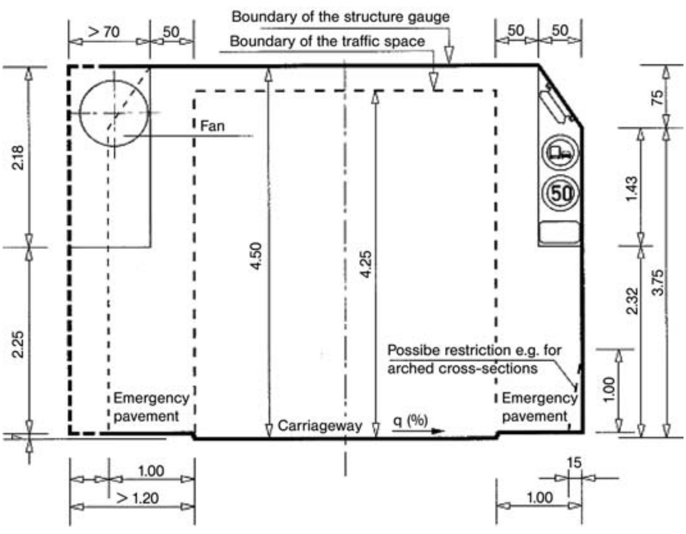

Figure 1-3 Outline of the clearance gauge in road tunnels (standard solution) [77].

The required headroom for road traffic is 4.50 m. For economic reasons, the sides of the outline are normally vertical, demanding a widening of the safety margin when the cross-slope gradient is steep. For circular cross-sections, on the other hand, it can be economic to tilt the clearance gauge with the carriageway. The outline at the sides can then be assumed to be vertical to the carriageway. It is not necessary in such cases to widen the safety margin.

The outline of the clearance gauge includes areas solely reserved for traffic. Emergency pavements are provided on each side of the carriageway, which are 1.00 m wide and have to have clear headroom of 2.25 m. These are separated from the carriageway with kerbs, normally 7 cm high. Part areas are assigned at a height > 2.25 m above the emergency side pavements, in which easily deformable furniture elements particularly traffic signs and notices can be located although these are only permitted to approach within 50 cm of the traffic gauge; jet fans required for ventilation have to be installed in niches or ceiling coves. Easily deformable light fittings are only permitted to approach within 50 cm of the traffic gauge at a height of > 3.75 m. If jet fans are located inside the normal structural dimensions, this results in widenings of the emergency pavements dependent on the diameter of the fans to be installed [77].

It is often practical to locate traffic signs on the end walls of breakdown bays. In exceptional cases, traffic signs can by located down to a minimum of 30 cm from the traffic gauge at a height > 2.25 m above the emergency pavements; but this does not apply where a widening of the emergency pavement has been provided for fans. If traffic signs have to be made with smaller dimensions than stated in the regulations [32], then this has to be agreed with the authority responsible for traffic management.

Light fittings are permitted to approach within 50 cm of the traffic gauge in exceptional cases when it can be ensured that a clear headroom of 4.10 m from the top of the emergency pavement to the underside of the light fitting is maintained at all points. Jet fans with external diameters ≤ 70 cm are permitted in exceptional cases to be located in the safety margin with a minimum distance at the side of ≥ 30 cm to the traffic gauge in the upper corners.

Gradient and cross-slope. According to the RAS-L [75], the gradient in uninhabited areas running through tunnels should be limited to 4 % if possible and a maximum of 2.5 % should be the intention, particularly for longer distances. The chimney effect, which also increases with increasing gradient, normally leads to higher longitudinal flow, which in case of fire can severely impair the rapid and effective removal of smoke by a ventilation system. In order to ensure road safety and due to the chimney effect, gradients steeper than 5 % should be avoided in road tunnels in uninhabited areas.

A minimum cross-slope of 2.5 % is specified for straight stretches in order to drain surface water [76]. Depending on the design speed, the cross-slope may have to be adapted to suit the curve radius [75]. In addition to these conventional requirements, the cross-slope of roads in tunnels has special significance in case of an accident. If a fire breaks out, any leaking flammable liquids have to be drained away as fast as possible, which is ensured by a steep cross-slope and high-capacity drainage. Slot channels with a capacity of 100 l/s should therefore be provided, with firestops spaced at max. 50 m [77].

1.2.2 Constructional measures for road safety in tunnels

Breakdown bays. Breakdown bays should be provided where the provision of hard shoulders is not economically justifiable. They are required in tunnels more than 900 m long, and under special conditions from 600 m (for example ≥ 4,000 HGV · km / bore and day) [77]. The end wall should have an angle of ≤ 1:3 in the travel direction (Fig. 1-4). It can be secured by suitable passive protection according to RPS [78]. Concrete protection walls should have an angle ≤ 1:3. In tunnels with two-way traffic, these requirements apply to both end walls.

Classification procedure. The following six parameters are used for the rock mass classification in the *RMR* system:

1. Uniaxial compression strength of the rock material.
2. Determination of the rock mass quality (*RQD*).
3. Discontinuity spacing.
4. Condition of the interfaces.
5. Water ingress.
6. Discontinuity orientation.

In order to used the geomechanical classification, the rock mass is split into sections, in which the condition of the rock has nearly the same properties. Although the rock mass as a natural material is not homogeneous, individual sections can be delineated according to the already mentioned aspects and used for the investigation (homogeneous sections). The characteristic properties of section are entered in a data sheet and evaluated with the aid of Table 2-16 and Table 2-17. It is important that Table 2-16 can be used independently of the orientation of any faults and the results are then corrected using Table 2-17 for their orientation and for the structure to be constructed.

Table 2-16 Classification parameters and their evaluation.

	Parameter	Range of values							
1	Strength of the intact rock (Mpa)	Point load strength index	> 10	4 – 10	2 – 4	1 – 2	-		
		Uniaxial compression strength	> 250	100 – 250	50 –100	25 – 50	5 – 25	1 – 5	< 1
	Rating		15	12	7	4	2	1	0
2	Drill core quality RQD [%]		90 – 100	75 – 90	50 – 75	25 – 50	< 25		
	Rating		20	17	13	8	3		
3	Spacing of discontinuities		> 2	0.6 – 2	0.2 – 0.6	0.06 – 0.2	< 0.06		
	Rating		20	15	10	8	5		
4	Condition of discontinuities		very rough surface, not continuous, no separation, unweathered wall rock	slightly rough surface, separations < 1 mm, weathered walls	slightly rough surface, separations < 1 mm, highly weathered walls	slickenside surface or slip < 5 mm or separations 1 – 5 mm continuous	soft slips > 5 mm or separations > 5 mm continuous		
	Rating		30	25	20	10	0		

Table 2-16 continued

	Parameter	**Range of values**					
5	Ground-water	Inflow per 10 m tunnel length [l/min]	none or	< 10 or	10 – 25 or	25 – 125 or	> 125 or
		Joint water pressure to principal stress	0 or	< 0.1 or	0.1 – 0.2 or	0.2 – 0.5 or	0.5 or
		General condition	completely dry	damp	wet	drips	streaming
	Rating		15	10	7	4	0

Table 2-17 Evaluation correction for the strike direction of the fault.

Strike and dip direction of the fault		**Specially favourable**	**Favourable**	**Acceptable**	**Unfavo-urable**	**Very unfa-vourable**
Evaluations	Tunnels and mines	0	up to 2	up to 5	up to 10	up to 12
	Foundations	0	up to 2	up to 7	up to 15	up to 25
	Slopes	0	up to 5	up to 25	up to 50	up to 60

If the results of the two tables are added, this gives a characteristic value, which enables assignment to a rock mass class with the aid of Table 2-18. The higher this value is, the better is the prevailing rock. The added range of values lies between 0 and 100, bad to very good.

In Table 2-19, the practical evaluation of the individual rock mass classes is explained using examples from engineering practice. Since the rock mass consists of the most varied sections, those with the most unfavourable faults for the future structure are decisive. Future construction measures have to be planned for this section, although the situation with regard to rock strength and other parameters may be good. In case two sections with different parameters dominate the entire cross-section, the evaluation numbers are weighted according to their area of occurrence and averaged to one characteristic value.

Table 2-18 Determination of rock mass classes from the overall evaluation.

Evaluation	**100 – 81**	**80 – 61**	**60 – 41**	**40 – 21**	**< 20**
Rock mass class	I	II	III	IV	V
Description	very good rock	good rock	acceptable rock	bad rock	very bad rock

Table 2-19 Evaluation of rock mass classes.

Rock mass class	I	II	III	IV	V
Average free stand-up time	self-supporting over 15 m for 20 years	self-supporting over 10 m for 1 year	self-supporting over 5 m for 1 week	self-supporting over 2.5 m for 10 hours	self-supporting over 1 m for 30 minutes
Cohesion of the rock mass [kPa]	> 400	300 to 400	200 to 300	100 to 200	< 100
Friction angle of the rock mass [°]	> 45	35 to 45	25 to 35	15 to 25	< 15

Strengths and limits. The RMR system is very simple to use; the classification parameters can be gained from analysis of drill cores or from geomechanical records. This procedure is applicable and adaptable to many situations in mining, for the stability of foundations and slopes and in tunnelling. The geomechanical classification is very well suitable for use in expert systems. On the other hand, the results of the RMR classification method tend to be conservative, which mostly leads to an over-dimensioning of support measures. This can be compensated by continuous monitoring during the construction period, with the evaluation system being adapted to local conditions.

2.4.2.5 Relationship between Q and RMR systems

Working from over 100 cases studies, it proved possible to establish an originally unintended, empirical relationship between the *RMR* and *Q* systems [23, 230, 22]. For tunnels, this can be given as:

$$RMR \approx 9 \cdot \text{In}Q + 44 \qquad \text{or} \qquad Q \approx e^{\frac{(RMR-44)}{9}}$$

Barton sees the relationship as given by the following formula:

$$RMR \approx 15 \cdot \log Q + 50 \qquad \text{or} \qquad Q \approx 10^{\frac{(RMR-50)}{50}}$$

The relationship between *Q* and *RMR* is also very well visible in Fig 2.8.

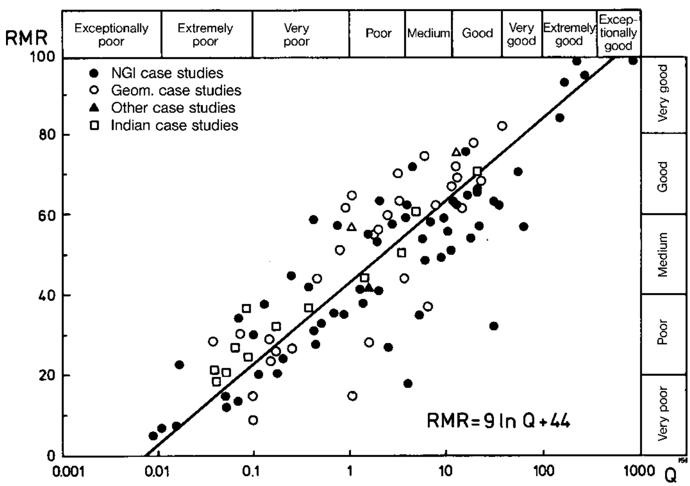

Figure 2-8 Relationship between RMR and Q systems.

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