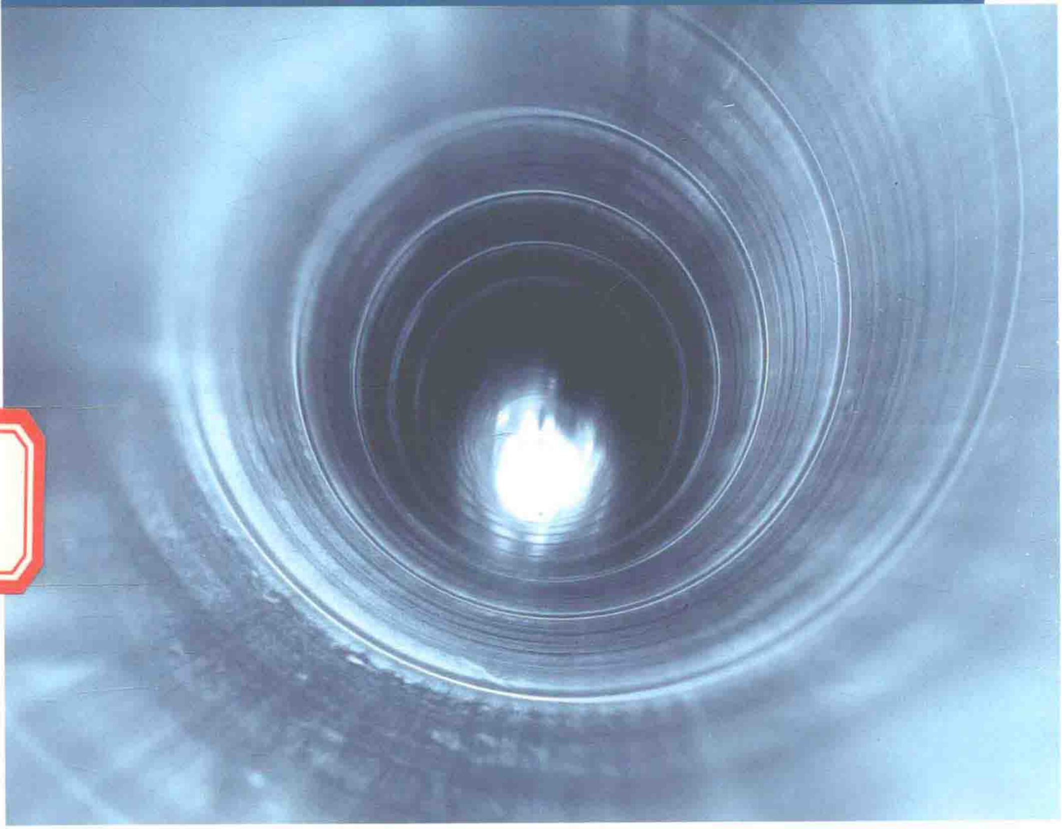
Prestressed Concrete-Lined Pressure Tunnels

Towards Improved Safety and Economical Design

Yos Simanjuntak



PRESTRESSED CONCRETE-LINED PRESSURE TUNNELS

Towards Improved Safety and Economical Design

DISSERTATION

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Summary

At the global scale, nearly two billion people are still lacking reliable electricity supply. Hydropower can be a source of sustainable energy, provided that environmental considerations are taken into account and economic aspects of hydropower design are addressed. Pressure tunnels are relatively expensive constructions, particularly when steel linings are used. Concrete linings can be economically attractive; however, their applicability is limited by the low tensile strength of concrete.

Techniques to improve the bearing capacity of concrete tunnel linings have become one of the interesting topics in hydropower research. One of the techniques available is through prestressing the cast-in-place concrete lining by grouting the circumferential gap between the concrete lining and the rock mass with cement-based grout at high pressure. As a consequence, compressive stresses are induced in the lining. This is meant to offset tensile stresses and avoid tendency for longitudinal cracks to occur in the lining due to radial expansion during tunnel operation. Moreover, as the grout fills discontinuities in the rock mass and hardens, the permeability of the rock mass is reduced. This is favourable in view of reducing seepage.

In order to maintain the prestressing effects in the concrete lining, the rock mass has to be firm enough to take the grouting pressure. The grouting pressure, taking into account a certain safety factor, should remain below the smallest principal stress in the rock mass. Since the prestress in the concrete lining is produced by the support from the rock mass, this technique is also called the passive prestressing technique. A classical approach to determine the bearing capacity of such tunnels does exist; but, it is based on the theory of elasticity assuming impervious concrete.

Due to the fact that the rock mass in nature is non-elastic and concrete is a slightly pervious material, doubts were fostered by experiences with tunnel failures resulting in loss of energy production, extensive repairs, and even accidents. Record shows that some of the tunnel failures are associated with hydraulic jacking or fracturing. While the former is the opening of existing cracks in the rock mass, the latter is the event that produces fractures in a sound rock.

The overall objective of this research is to investigate the mechanical and hydraulic behaviour of pressure tunnels. By means of a two-dimensional finite element model, the load sharing between the rock mass and the concrete lining is explored.

This research deals with the effects of seepage on the bearing capacity of pre-stressed concrete-lined pressure tunnels. A new concept to assess the maximum internal water pressure is introduced. The second innovative aspect in this research is to explore the effects of the in-situ stress ratio in the rock mass on the concrete lining performance. The rock mass supporting the tunnel is distinguished based on whether it behaves as an elastic isotropic, elasto-plastic isotropic or elastic transversely isotropic material. In the final part, this research focuses on the cracking of concrete tunnel linings. A step-by-step calculation procedure is proposed so as to quickly quantify seepage and seepage pressure associated with longitudinal cracks, which is useful for taking measures regarding tunnel stability.

If the assumption of elastic isotropic rock mass is acceptable, this research suggests that the load-line diagram method should only be used if it can be guaranteed that no seepage flows into the rock mass. Otherwise, seepage cannot be neglected when determining the bearing capacity of prestressed concrete-lined pressure tunnels.

In cases of pressure tunnels embedded in an elasto-plastic isotropic rock mass, the Hoek-Brown failure criterion is applicable for investigating the behaviour of the rock mass. When pressure tunnels are constructed in an inherently anisotropic rock mass, the rock mass can be idealized as an elastic transversely isotopic material. Regarding the behaviour of the concrete lining, the combined Rankine-Von Mises yield criteria can be used. While the former controls the response of the concrete lining in tension, the latter in compression.

When dealing with a three-dimensional problem of tunnel excavation and eventually the load transferred to the support, the limitation of two-dimensional models can be solved by means of the convergence-confinement method. However, this is not the case when the in-situ stresses in the rock mass are non-uniform. In such cases, the simultaneous tunnel excavation and support installation is acceptable provided that the radial deformations at the shotcrete-concrete lining interface are reset to zero to avoid the lining being influenced by the previous deformations during prestressing.

It is evident that the load sharing between the rock mass and the lining determines the bearing capacity of prestressed concrete-lined pressure tunnels. Particularly in the lining, longitudinal cracks can occur along the weakest surface that is submitted to the smallest total stress in the rock mass. When pressure tunnels embedded in elasto-plastic isotropic rock mass, longitudinal cracks may occur at the sidewalls if the in-situ vertical stress is greater than the horizontal. If the in-situ horizontal stress is greater than the vertical, cracks will occur at the roof and invert.

When pressure tunnels are embedded in transversely isotropic rocks and the in-situ stresses are uniform, the locations of longitudinal cracks in the lining are influenced by the orientation of stratification planes. If the stratification planes are horizontal and the in-situ vertical stress is greater than the horizontal, cracks can occur at the sidewalls; whereas if the stratification planes are vertical and the in-situ horizontal stress is greater than the vertical, cracks can occur at the roof and invert. When the stratification planes are inclined and the in-situ stresses are non-uniform, longitudinal cracks will take place at the arcs of the lining, and their locations are influenced by the combined effects of the in-situ stress ratio and the orientation of stratification planes in the rock mass.

Since crack openings in the lining are difficult to control with the passive prestressing technique, it is essential to maintain the lining in a compressive state of stress during tunnel operation. The attractive design criteria for prestressed concrete-lined pressure tunnels are therefore: avoiding longitudinal cracks in the lining, limiting seepage into the rock mass, and ensuring the bearing capacity of the rock mass supporting the tunnel. All in all, this research demonstrates the applicability of a two-dimensional finite element model to investigate the mechanical and hydraulic behaviour of pressure tunnels. Remaining challenges are identified for further improvement of pressure tunnel modelling tools and techniques in the future.

Samenvatting

Meer dan twee miljard mensen op de wereld ontberen betrouwbare energievoorziening en waterkracht is een manier van duurzame energieopwekking die daarin kan voorzien. Dit betekent dat nauwe eisen moeten worden gesteld aan het economisch ontwerpen van waterkracht-centrales. Leidingsystemen, met name de valpijp, spelen hierbij een belangrijke rol. Deze zijn vaak uitgevoerd in staal wat relatief gezien dure onderdelen van de constructie zijn die hun weerslag vinden in de bouw- en onderhoudskosten alsmede in de duurzaamheid van de energievoorziening als geheel. Door deze leidingsystemen uit te voeren in voorgespannen beton kunnen mogelijk kosten worden bespaard. Een van de mogelijkheden daarbij is om de ruimte tussen de betonwand en de rotsmassa op te vullen met een groutmassa onder grote druk. Op die manier worden de trekspanningen in langsrichting gereduceerd en kunnen barsten in radiaalrichting worden voorkomen. Bovendien wordt de doorlatendheid nabij de leiding gereduceerd, wat lekkage kan voorkomen en de stabiliteit vergroot.

Om de voorspanningseffecten van de betonwand te behouden, dient de rotsmassa stevig genoeg te zijn om de groutdruk aan te kunnen. De groutdruk dient, met inachtneming van een bepaalde veiligheidsmarge, onder de kleinste primaire spanningen in de rotsmassa te blijven. Aangezien de voorspanning in de betonwand wordt verkregen door middel van ondersteuning van de rotsmassa, staat deze techniek ook wel bekend als een passieve voorspanningstechniek. Een klassieke benadering om het draagvermogen van dergelijke tunnels te bepalen bestaat weliswaar, maar deze is gebaseerd op de elasticiteitstheorie en gaat uit van ondoordringbaar beton.

Vanwege het feit dat de rotsmassa in de natuur niet-elastisch is en beton een enigszins doorlatend materiaal is, zijn er twijfels ontstaan naar aanleiding van ervaringen met het falen van tunnels (valpijpen), welke resulteerden in verlies van energieproductie, dure reparaties en zelfs ongelukken. In sommige gevallen is het falen van tunnels in verband gebracht met hydraulic jacking of hydraulic fracturing. De eerstgenoemde is het verder opengaan van bestaande scheuren in de rotsmassa en de laatste is een oorzaak voor het ontstaan van scheuren in de intacte rotsmassa.

Het doel van dit onderzoek is om na te gaan hoe leidingsystemen van voorgespannen beton zich gedragen. Door gebruik te maken van tweedimensionaal eindige elementen berekeningen worden de krachten bepaald die hierbij een rol spelen. Het eerste deel van het onderzoek gaat na welke processen het draagvermogen beïnvloeden en lekkage veroorzaken. Daarbij wordt een nieuw concept geïntroduceerd om de interne waterdruk te bepalen.

Een tweede innovatie in dit onderzoek richt zich op het beter berekenen van het draagvermogen van de constructie door elasto-plastisch gedrag van de rotsmassa en effecten van anisotropie na te gaan. Met name dit laatste vraagt om een betere beschrijving van stratificatie-effecten in de omringende rotsmassa. Het laatste deel van dit onderzoek richt zich op het proces van scheurvorming in de betonwanden. Er wordt een eenvoudige methode voorgesteld om de lekkage vast te stellen en te kwantificeren zodat maatregelen kunnen worden genomen om de veiligheid en stabiliteit van de tunnel te garanderen.

Als de aanname van een elastisch isotrope rotsmassa acceptabel is, dan geeft dit onderzoek aan dat de load-line diagram methode alleen gebruikt moet worden indien gegarandeerd kan worden dat er geen lekkage plaats vindt in de rotsmassa. Indien dit niet gegarandeerd kan worden, dan kan de lekkage niet genegeerd worden bij het bepalen van het draagvermogen van voorgespannen betontunnels.

In geval voorgespannen betontunnels geacht worden ingebed te zijn in een elasto-plastische isotrope rotsmassa, is het Hoek-Brown faalcriterium van toepassing om het gedrag van de rotsmassa te onderzoeken. Als betontunnels gebouwd worden in een anisotrope rotsmassa, dan kan de rotsmassa voorgesteld worden als een, in dwarsrichting isotroop, elastisch materiaal. Met betrekking tot het gedrag van de betonwanden kan het gecombineerde Rankine-Von Mises criteria aangehouden worden. Waar de eerste de reactie van de betonwanden onder trekspanning controleert, controleert de laatste de compressie.

In het geval van een driedimensionaal probleem van tunneluitgraving waarbij de belasting wordt overgedragen op de ondersteuning, kunnen de beperkingen van een tweedimensionaal numeriek model verholpen worden door middel van de convergence-confinement methode. Echter, dit is niet het geval als de in-situ belastingen in de rotsmassa niet-uniform zijn. In zulke gevallen is het tegelijkertijd uitgraven en ondersteunen van de tunnel alleen acceptabel indien de radiale deformaties van de betonwanden verwaarloosbaar kunnen worden geacht, om te voorkomen dat de betonwanden beïnvloed worden door voorgaande deformaties tijdens het voorspannen.

Het is evident dat de verdeling van de belasting tussen de rotsmassa en de betonwand het draagvermogen bepaalt van de voorgespannen betontunnels. Vooral in betonwanden kunnen scheuren in de langsrichting ontstaan op plaatsen waar het zwakste oppervlak wordt blootgesteld aan de kleinste totale druk in de rotsmassa. Wanneer tunnels ingebed zijn in elasto-plastische isotrope rotsmassa's, kunnen scheuren in de langsrichting ontstaan in de zijwanden zodra de verticale in-situ belasting groter is dan de horizontale belasting. Wanneer de horizontale in-situ belasting groter is dan de verticale, ontstaan scheuren in het dak en de vloer van de tunnel.

Wanneer leidingsystemen ingebed zijn in dwarsrichting isotrope rotsmassa's en de in-situ belastingen zijn uniform, worden scheuren in de langsrichting in de wanden beïnvloed door de oriëntatie van stratificatie in de omringende rotsmassa. Als de stratificatie horizontaal is, en de verticale in-situ belasting groter is dan de horizontale, kunnen scheuren ontstaan in de zijwanden; waar als de stratificatie verticaal is en de horizontale in-situ belasting groter is dan de verticale, ontstaan scheuren in het dak en de vloer van de tunnel. Wanneer de stratificatie gekanteld is en de in-situ belastingen non-uniform zijn, ontstaan scheuren in de langsrichting in de bogen van de betonwanden en hun locaties zijn beïnvloed door de gecombineerde effecten van in-situ belastingen en de stratificatie in de omringende rotsmassa. Vandaar dat er vaak als ontwerpcriterium naar wordt gestreefd om scheurvorming geheel te voorkomen, lekkage te beperken en zorg te dragen dat het draagvermogen van de rotsmassa de tunnel ondersteunt. Dit proefschrift toont de toepasbaarheid van een tweedimensionaal eindige elementen model aan om het mechanische en hydraulische gedrag van voorgespannen betontunnels te onderzoeken. Uiteraard blijven er verdere verbeteringen mogelijk, zoals aangegeven in dit proefschrift.

Contents

1 General Introduction

1.1. Background

A pressure tunnel in general is an underground excavation aligned along an axis and conveys high pressurized water from one reservoir to another reservoir or to turbine. As one of the hydropower components, pressure tunnels represent an important share of the total investment for hydropower plant. Without doubt, concrete linings have nowadays become the most attractive type of lining in view of construction time and economic benefits. Nevertheless, such linings are vulnerable to cracking during tunnel operation due to the low tensile strength of concrete.

By injecting the circumferential gap between the concrete lining and the rock mass with grout at high pressure, the bearing capacity of concrete-lined pressure tunnels can be improved. This technique, which is also known as the passive prestressing technique, can produce adequate compressive stresses in the lining to suppress tensile stresses and to avoid the opening of longitudinal cracks.

Principally, the lining prestressing is executed after the completion of consolidation grouting. This is necessary in order to provide stability to the underground opening after the tunnel excavation. Regarding the prestressing, the level of grouting pressure injected into the gap has to remain below the smallest principal stress in the rock mass. A full contact between the concrete lining and the rock mass can be achieved as the grout fills the gap and hardens. This provides a continuous load transfer between the lining and the rock mass, which is favourable for tunnel stability. Other benefits of this technique include homogenization of material behaviour and eventually stress pattern around the tunnel, and reduction of seepage into the rock mass.

Despite its popularity, the achievement of the passive prestressing technique depends on the characteristics of the rock mass. Due to fissures and discontinuities, the rock mass is obviously pervious. Even uncracked concrete linings are not totally impervious as often assumed by tunnel designers. Pores in concrete permit seepage pressures that act not only in the lining but also in the rock mass. Seepage pressures in the rock mass can affect the tunnel deformations and therefore should not be neglected.

Aside from taking into account seepage effects, the main novelty of this research is the determination of the load sharing between the rock mass and the lining, which has yet to be understood particularly when assessing the maximum internal water pressure. In view of the applicability of the finite element method in dealing with complex concrete and rock problems, finite element models can be used to address this task. Nevertheless, regardless of simplifications, analytical solutions should not be overlooked as they reflect both tunnelling tradition and design experience. A contribution towards an effective application of a two-dimensional finite element model on the design of concrete-lined pressure tunnels is presented in this dissertation.

1.2. Research Questions

In overall, this dissertation covers a series of investigations on the mechanical and hydraulic behaviour of prestressed concrete-lined pressure tunnels. It focuses on a deep, circular and straight ahead tunnel, which allows the application of plane strain, two-dimensional finite element models.

As the worst scenario for prestressed concrete-lined pressure tunnels, this research is dedicated for cases where tunnels are situated above the groundwater level. Without the groundwater, the bearing capacity of concrete-lined pressure tunnels depends solely on the prestressing works and the support from the rock mass. Distinction is made based on whether the rock mass behaves as an elasto-plastic isotropic or elastic anisotropic material. As the main research topics, the following research questions arise:

- What is the influence of lining permeability and the rationale to assess the maximum internal water pressure for prestressed-concrete-lined pressure tunnels?

- How different is the behaviour of pressure tunnels embedded in an elasto-plastic isotropic rock mass subjected to non-uniform in-situ stresses compared to those subjected to uniform in-situ stresses? Which parameter governs the tunnel bearing capacity?

- In cases of transversely isotropic rocks, how does the interplay between the in-situ stress ratio and the orientation of transverse isotropy affect the lining performance? Where are the potential locations of longitudinal cracks in the lining?

- Once longitudinal cracks occur in the lining, what is the procedure to estimate seepage associated with cracks around the tunnel? How does the saturated zone develop after the lining cracking?

- When using two-dimensional finite element models, what are the most important aspects for modelling of pressure tunnels? Which process is not considered in the model and affects the accuracy?

1.3. Research Objectives

This research aims to provide insights into how to determine the bearing capacity of prestressed concrete-lined pressure tunnels. Specific objectives are:

1. to develop a concept to assess the maximum internal water pressure of prestressed concrete-lined pressure tunnels and at the same time to quantify the amount of seepage into the rock mass;

2. to extend the applicability of two-dimensional finite element models to reveal stresses and deformations around the tunnel as a result of tunnelling construction processes, that consists of tunnel excavation, installation of support, and lining prestressing as well as of the activation of internal water pressure;

3. to identify potential locations where longitudinal cracks can occur in the concrete lining and introduce a procedure to estimate the seepage associated with cracks as well as its reach into the rock mass;

4. to derive the design criteria for prestressed concrete-lined pressure tunnels.

1.4. Dissertation Outline

Each chapter of this dissertation is written as a standalone article. In each chapter, a general background of prestressed concrete-lined pressure tunnels may be repeated, however with different emphases depending on the topic discussed. The five main chapters are Chapter 3, 4, 5, 6 and 7. While Chapter 3, 4, 5, and 7 already have been published elsewhere, Chapter 6 is under review and consideration for publication as another research paper.

Chapter 1 introduces the scope of this research. In addition to research questions, the specific objectives are listed. The outline of the dissertation is presented with an overview of content and structure.

Chapter 2 summarizes the state-of-the-art review of the design of pressure tunnels. Starting with the flow chart to quickly determine the types of pressure tunnel linings, historical development of prestressed concrete-lined pressure tunnels is presented. Furthermore, aspects in the design of prestressed concrete-lined pressure tunnels are highlighted. The knowledge gaps are identified.

Chapter 3 introduces the method to determine the bearing capacity of prestressed concrete-lined pressure tunnels in an elastic isotropic rock mass. Existing formulae to assess the prestress- and seepage- induced hoop strains in the final lining are recalled. A new criterion to assess the maximum internal water pressure is introduced. The effects of grouted zone on the stability of pressure tunnels are explored.

Chapter 4 investigates the behaviour of prestressed concrete-lined pressure tunnels in an elasto-plastic isotropic rock mass subjected to uniform in-situ stresses. It covers the modelling of tunnel excavation, support installation, prestressing of final lining and the activation of internal water pressure. Special attention is given to overcome the limitation of two-dimensional models when dealing with a three-dimensional problem of tunnel excavation. In view of model validation, the numerical results are compared to the available theory.

Chapter 5 further investigates the behaviour of prestressed concrete-lined pressure tunnels in an elasto-plastic isotropic rock mass. However, the tunnels being examined are embedded in the rock mass whose in-situ stresses are different in the vertical and horizontal direction. Two cases are analysed, based on whether the in-situ vertical stress is greater than the horizontal, or not. Locations where longitudinal cracks can occur in the final lining are identified, which is useful for taking measures regarding tunnel tightness and stability.

Chapter 6 deals with the behaviour of prestressed concrete-lined pressure tunnels in elastic transversely isotropic rocks. It explores the interplay between the orientation of stratification planes and the in-situ stress ratio, which is frequently ignored in the design of pressure tunnels. As well as potential locations of longitudinal cracks in the final lining, this chapter investigates the effect of anisotropic rock mass permeability on the saturated zone around the tunnel.

Chapter 7 focuses on cracking in pressure tunnel concrete linings. The concept to assess the internal water pressure resulting in longitudinal cracks is oriented towards the optimum utilization of the tensile strength of concrete. A simple approach to quantify seepage and seepage pressures associated with longitudinal cracks is introduced. However, numerical models are needed so as to capture the saturated zone in the rock mass as a result of lining cracking.

Chapter 8 summarizes the main findings of the research, arriving at conclusions and discussing remaining challenges and future works.

2 Literature Review

This chapter briefly presents the historical development of the design of prestressed concrete-lined pressure tunnels. It provides a flow chart for an easy identification of the types of tunnel linings as well as the existing design approaches. The important aspects in the design of prestressed concrete-lined pressure tunnels are outlined. The gaps of knowledge, which need to be addressed in this dissertation, are identified.

2.1. General Design Criteria

The types of pressure tunnel linings in general depend on the characteristics of the rock mass covering the tunnel and the groundwater conditions. As a result, pressure tunnels may not be uniform in construction, but consist of different types of linings over their entire length. Fig. 2.1 shows the flow chart to allow for a quick determination of the types of pressure tunnel linings.

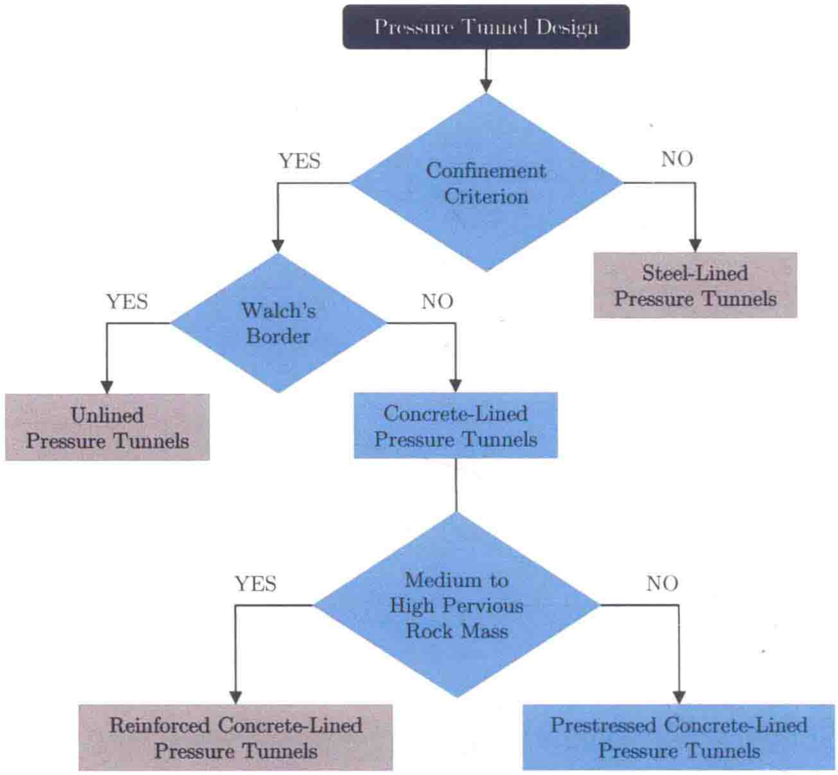

Fig. 2.1. Flowchart to Determine the Types of Pressure Tunnel Linings

As long as the smallest principal stress in the rock mass is higher than the internal water pressure, a steel lining is not necessary. Instead, pressure tunnels can be left unlined or merely lined with shotcrete for stability purposes if the rock mass is impervious and the external water pressure induced by the groundwater is higher than the internal water pressure. While the former criterion is known as the confinement criterion, the latter is called the Walch's border (Stini, 1950).

When the confinement criterion is satisfied but the Walch's border is not, concrete linings can be installed onto the shotcrete or the rock mass as an alternative to steel linings. However, the applicability of concrete-lined pressure tunnels is limited due to the low tensile strength of concrete.

Depending on the permeability of the rock mass, the bearing capacity of concrete linings against tensile stresses can be improved. If the rock mass is too pervious when compared to the concrete lining, an economical steel reinforcement can be embedded in the lining in addition to avoiding the occurrence of single wide cracks (Schleiss, 1997b). Like in most reinforced concrete structures, steel reinforcement in the lining can provide assurance against cracking. It distributes longitudinal cracks in the lining in a controlled manner.

If the rock mass is not too pervious, a carefully prestressed concrete lining can be adequate. A concrete lining can be prestressed either by grouting the circumferential gap between the lining and the rock mass at high pressure (Seeber, 1984; 1985a; 1985b) referred to as the passive prestressing technique, or by using individual tendons running in or around the concrete lining (Matt et al., 1978) known as the active prestressing technique. It has to be emphasized that prestressed concrete linings are not impervious. These types of linings allow seepage into the rock mass, which can influence tunnel deformations.

2.2. Historical Development of Prestressed Concrete-Lined Pressure Tunnels

The design method of prestressed concrete-lined pressure tunnels was first introduced by Kieser (1960). He introduced the so-called Kernring (core ring) lining as a substitute for steel linings. His method is characterized by the fact that the circumferential gap between the core ring and the rock mass is grouted with cement mortar which sets under pressure. The effect of prestressing in the core ring can be quantified by using the thick-walled cylinder theory (Timoshenko et al., 1970).

Thereafter, Lauffer and Seeber (1961) introduced the Tiroler Wasserkraftwerke AG (TIWAG) gap grouting method. Similar to the Kieser method, the concrete lining is prestressed against the rock mass by injecting cement-based grout at high pressure into the circumferential gap between the rock and the concrete lining.

In the gap grouting method of TIWAG, the grout is injected through the circumferential and axial pipes. These pipes, which are perforated, have valves and are placed at defined intervals along the tunnel wall before concreting the lining. As a result, the grout is more precisely distributed and an overall grouting of the circumferential gap between the rock and the lining can be guaranteed. As soon as the desired compressive stress in the concrete lining is obtained, the next pipe is connected to the pump. Another advantage of such arrangements is that the injection can be repeated as many times as required.

To facilitate the opening of the circumferential gap between the concrete lining and the shotcrete, the shotcrete surface can be covered with a bond breaker of whitewash or, a synthetic foil before concreting the final lining. Thereby, the grout will deposit in the circumferential gap and at the same time penetrates and seals fissures of the adjacent rock mass as the grout hardens.