出國報告（出國類別：開會）

高放射性廢棄物最終處置技術交流研討會（內部參考）

服務機關： 台灣電力公司
核能後端營運處
姓名職稱： 李在平 地質調查專員
邱琮翔 地質調查專員

派赴國家/地區： 美國西雅圖

出國期間： **107** 年 **6** 月 **16** 日～**107** 年 **6** 月 **28** 日

報告日期： **106** 年 **8** 月 **24** 日

行政院及所屬各機關出國報告提要

出國報告名稱：高放射性廢棄物最終處置技術交流研討會

頁數 72　含附件：□是 □否

出國計畫主辦機關/聯絡人/電話

台灣電力公司/陳德隆/(02)2366-7685

出國人員姓名/服務機關/單位/職稱/電話

李在平/台灣電力公司/核能後端營運處/地質調查專員/(02)2365-7210

邱琮翔/台灣電力公司/核能後端營運處/地質調查專員/(02)2365-7210

出國類別：□1 考察 □2 進修 □3 研究 □4 實習 ■5 開會 □6 其他

出國期間：107 年 6 月 16 日　至 107 年 6 月 28 日

派赴國家/地區：　美國/西雅圖

報告日期：107 年 8 月 14 日

關鍵詞：離散裂隙網路、岩石力學、用過核子燃料最終處置

內容摘要：（二百至三百字）

台電公司執行用過核子燃料最終處置計畫，現階段參考瑞典發展之 KBS-3 處置概念，以歷年來全國地質調查取得之潛在處置母岩相關特性參數，建立離散裂隙網路(DFN)模式，並進行相關地下水流場、核種傳輸途徑與裂隙截切模式等相關模式分析，進行全系統安全評估並據以完成「我國用過核子燃料最終處置技術可行性評估報告(SNFD2017 報告)」並提報主管機關。本次受邀赴美國西雅圖參加第 52 屆美國岩石力學年會暨第 2 屆離散裂隙網路工程研討會，發表 SNFD2017 報告相關成果並與國際專家技術交流，國際專家亦提供技術發展經驗，可作為處置計畫相關技術規劃之參考。

本文電子檔已傳至公務出國報告資訊網（https://report.nat.gov.tw/reportwork）

摘要

台電公司執行用過核子燃料最終處置計畫，現階段參考瑞典發展之 KBS-3 處置概念，以歷年來全國地質調查取得之潛在處置母岩相關特性參數，建立離散裂隙網路(DFN)模式，並進行相關地下水流場、核種傳輸途徑與裂隙截切模式等相關模式分析，進行全系統安全評估並據以完成「我國用過核子燃料最終處置技術可行性評估報告(SNFD2017 報告)」並提報主管機關，本階段工作主要為處置技術與安全評估技術之建立，相關工作並未涉及最終處置場選址作業。

台電公司受邀參加由美國岩石力學學會於美國西雅圖舉辦的第 52 屆美國岩石力學年會暨第 2 屆離散裂隙網路工程研討會，會中就土木工程、地質科學與採礦、地球物理勘探、石油工程、二氧化碳封存、地熱、廢棄物處置等領域的應用，以及 DFN 技術之基礎理論、工程應用、技術發展等分項探討，並進行廣泛的技術交流。

台電公司偕同核能研究所及工業技術研究院專家，以 SNFD2017 報告內容發表相關論文，據以說明我國最終處置技術發展現況，相關調查與安全評估分析成果，獲與會專家認同，專家亦建議應持續關注國際最新技術發展，就既有之模型持續精進與提升安全評估技術。透過與國外專家學者之技術交流，將有助於處置技術發展與規劃，對處置計畫之推動有相當大之助益。

目錄

圖目錄

表目錄

壹、出國目的

目前國際間高放射性廢棄物最終處置技術與安全評估的發展，主要著重在結晶岩類與沉積岩類 2 大岩類上，其中又以瑞典、芬蘭等國所採用的結晶岩深層地質處置概念，位居國際技術領先地位。結晶岩深層地質處置概念，係以結晶岩作為天然障壁，以其堅硬且緻密的岩體特性，將放射性廢棄物長期封存於岩體內，除此之外，亦利用其極低的透水性，阻絕放射性核種傳輸的媒介－水，降低放射性核種外釋的機率，以達到長期的輻射安全目標。

在進行結晶岩深層地質處置概念的安全評估時，因核種傳輸的主要媒介為水，如何就既有的調查資料進行地下水的流場及溶質傳輸評估，是最重要的課題。一般完整的結晶岩體中，因岩石礦物顆粒緻密故本身透水性極低，岩體內的裂隙即容易成為地下水流的通道。故瞭解岩體內的裂隙特性，為評估核種傳輸最重要的工作，目前國際間，多採用離散裂隙網路(Discrete Fracture Network, DFN)方法，作為評估結晶岩體內裂隙分布特性研究。

台電公司發展「用過核子燃料最終處置」相關技術，目前參考瑞典核燃料及廢棄物管理公司(Swedish Nuclear Fuel and Waste Management Company, SKB)所發展的 KBS-3 處置概念，發展及建立國內的處置技術。目前以國內既有之結晶岩質處置母岩的地質特性，以 KBS-3 處置概念為基礎，完成「我國用過核子燃料最終處置技術可行性評估報告(SNFD2017 報告)」，報告以歷年現地調查結果建立 DFN 模式，並據以評估地下水流場、傳輸途徑及裂隙截切模式，完成安全評估相關成果，參加本次會議可向參與單位展示我國目前之狀況與技術能力，以作為未來深入交流與技術合作之基礎。

本次會議與會人員包括其他國家放射性廢棄物最終處置專責機構(如：加拿大 NWMO、捷克 SURAO、英國 NDA)或研究單位(如：法國 CNRS、美國 Lawrence Berkley, Los Alamos, Sandia National Lab.)等單位，並發表相關研究成果，參加本次會議可瞭解國際相關技術之發展現況，作為我國未來技術規劃之參考，亦可瞭

解其技術能力，探討國內研究團隊參與之可能性，作為未來技術引進及人才培育之管道。

放射性廢棄物處置技術發展日新月異，除可透過各國發表之技術報告了解技術發展現況外，亦可藉由參加國際研討會，直接獲取國際最新發表之研究成果，並透過與國際專家的直接溝通及討論，更能進一步瞭解相關研究成果之細節，亦可讓國際專家瞭解我國現況，有助於國內高放射性最終處置計畫之推動，同時透過與各國專家學者交流，有助協助處置計畫與國際接軌。

貳、出國過程

自 107 年 6 月 16 日出發，迄 6 月 28 日返國(共計 13 天)，參加由美國岩石力學學會(American rock mechanics association, ARMA)於西雅圖威斯汀酒店(Westin Seattle Hotel 如圖 1)召開之「第 52 屆美國岩石力學年會(52nd US Rock Mechanics/Geomechanics Symposium, RM/GS 2018)」，聽取各國專家在岩石力學工程技術應用與研究成果，且與隨後抵達之用過核子燃料最終處置計畫團隊成員：行政院原子能委員會核能研究所曾漢湘研究員及黃鈺翔工程師、工業技術研究院黃淞洋副研究員及國立中正大學劉台生副教授，共同參加「第 2 屆離散裂隙網路工程研討會(2nd International Discrete Fracture Network Engineering Conference, DFNE 2018)」，並於會議上發表論文及聽取離散裂隙網路技術的最新發展與應用。會後前往位於西雅圖近郊雷德蒙德(Redmond)，拜訪開發離散裂隙網路模擬軟體 FracMan 的 Golder 公司(Golder Associates Inc.)，就軟體使用心得及其模式應用的軟體設定進行意見交流，並討論可行的解決與替代方法，出訪行程及工作內容如表 1 所示：

表 1：出訪行程及工作內容

日期	地點與行程	工作內容
6 月 16 日(六)	臺北到美國西雅圖	往程
6 月 17 日(日)	美國西雅圖	參加 RM/GS 2018
6 月 18 日(一)		
6 月 19 日(二)		
6 月 20 日(三)		參加 DFNE 2018
6 月 21 日(四)		
6 月 22 日(五)		
6 月 23 日(六)		資料整理
6 月 24 日(日)		
6 月 25 日(一)		拜訪 Golder 公司
6 月 26 日(二)	美國西雅圖到美國舊金山	返程(轉機)
6 月 27 日(三)	美國舊金山到臺北	返程
6 月 28 日(四)		

叁、工作內容

國際上仍持續進行處置技術發展的處置母岩，依其岩石特性大致可分為：沉積岩類(泥質岩、泥質石灰岩、輕度變質之沉積岩)、蒸發岩類(鹽岩)及結晶岩類(花崗岩類)等 3 類，而目前又以結晶岩類與沉積岩類受多數國家所採用，台電公司於 2017 年所提出的「我國用過核子燃料最終處置技術可行性評估報告」指出我國境內的潛在處置母岩包括：結晶岩類(花崗岩為主)、西南部泥岩及中生代基盤岩類等 3 種，分屬於國際分類的結晶岩類及沉積岩類。就結晶岩類而言，花崗岩體因具有較高的岩石力學強度易於施工、岩體的透水性極低等優點，被多國選擇作為處置母岩並發展處置相關技術。此外，水為放射性核種的主要傳輸媒介，若岩體中存在地下水，因花崗岩本身透水性極低，地下水僅能透過岩體內連通的裂隙網路流動，因此如何有效將岩體內的裂隙特徵化，以評估核種的傳輸途徑是相當重要的研究議題，亦是我國用過核子燃料最終處置計畫長期發展的重點項目。

本次受離散裂隙網路工程研討會主席 Bill Dershowitz 博士的邀請，希望能將我國在裂隙岩體的研究成果與國際社會分享，因此職李在平與邱琮翔專員分別投稿了 1 篇離散裂隙網路分析技術的應用論文，並偕同計畫執行團隊原子能委員會核能研究所與工業技術研究院的專家共同參與，與各國與會專家進行深度交流，展現並精進本公司團隊在最終處置技術的研發實力。由於本次研討會併同美國岩石力學年會舉辦，而岩石力學與大地工程相關技術(地下設施設計、開挖等)亦屬處置計畫重要的技術項目，故本次出國除參加離散裂隙網路工程研討會外，亦併同參加美國岩石力學年會，蒐集美國岩石力學相關領域最新研究技術與研究成果。於研討會結束後，前往 Golder 公司(Golder Associates Inc.)，就過往使用 FracMan 軟體時，在軟體使用上遇到的困難與模式設定上的應用進行意見交流，並與目前 FracMan 美國部門的負責人 Doo-Hyun Lim 博士及高級工程師石春美博士，討論上述問題可行的解決與替代方法，本次出國工作內容說明如下：

一、第 52 屆美國岩石力學年會

美國岩石力學學會舉辦的美國岩石力學年會，是國際上重要的岩石力學領域研討會，除了美國外，亦有來自世界各地的學術單位與研究機構共數百名學者專家與會。本屆會議已是第 52 次舉辦，研討會時間為 2018 年 6 月 17 日至 6 月 20 日，討論議題包括土木工程、地質科學與採礦、地球物理勘探、石油工程、二氧化碳封存、地熱、廢棄物處置等領域的應用，此外，受惠於水力壓裂技術的進步，頁岩油及天然氣的大量開採導致開挖及存量評估需求大量增加，而大量的水力壓裂開採方法也產生大量的現地應力數據，故本次會議主題偏重在岩石力學與地質力學的最新進展(New and Exciting Advances in All Areas of Rock Mechanics and Geomechanics)，包括水力破裂的試驗與模擬、邊坡穩定分析、儲集層地質力學、開礦過程地震活動與地表控制、隧道工程等。會議進行方式則依議題，分別以口頭宣讀或海報呈現，大會並規劃每天面對面的交流時間，讓海報作者能與參與者進行深入討論(如圖 2)。

由於會議討論的議題廣泛，以下分就與計畫需求相關所蒐集之研究資料進行說明：

圖 1 ：會議地點 Westin Seattle Hotel

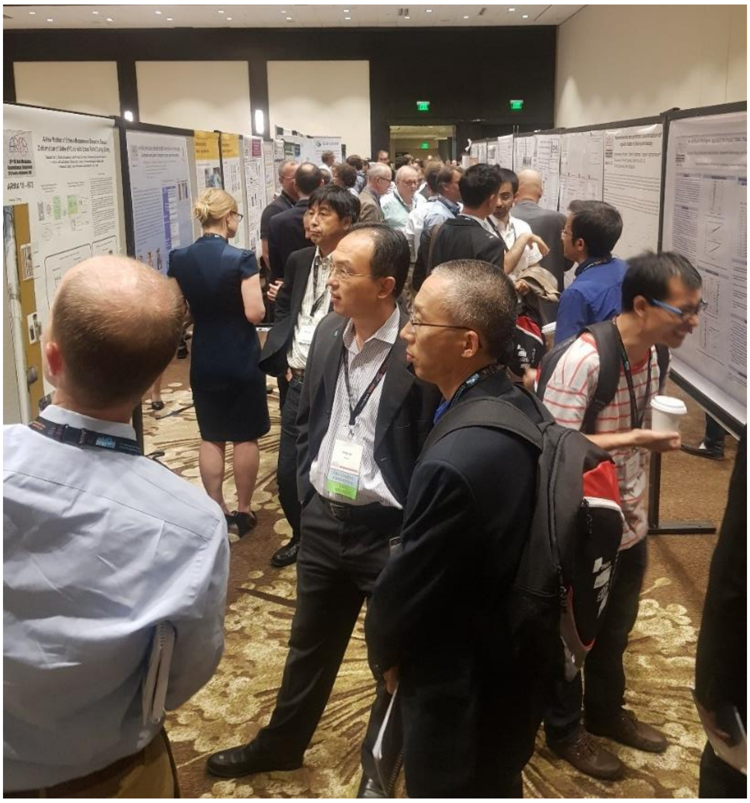


圖 2 ：海報論文發表與交流

（一）數值模擬與分析模式

在處置設施的設計中，母岩材料的岩石力學特性，是直接影響處置坑道的開挖與工程設計的重要參考依據。針對現地調查資料進行數據整合分析，從而獲取岩石力學概念模式所需之關鍵參數，進而建構合理的數值分析模式皆是目前處置計畫所發展的項目。針對數值模擬與模式分析的項目，與處置計畫相關的研究論文包括：

1. 結晶岩中內不同深度雙層用過核子燃料處置場之近場與遠場熱力耦合分析 (Near-field and far-field thermal-mechanical modelling of a two-level deep geological repository for the used nuclear fuel in crystalline rock., ARMA18-1373, 圖 3)

   本研究為加拿大核廢棄物營運機構(Nuclear Waste Management Organization, NWMO)委託 Golder 公司進行。加拿大目前情況與我國相似，用過核子燃料最終處置仍處於選址階段，也同樣選定花崗岩作為潛在的處置母岩，考量處置母岩的岩體大小以及地質構造，希望能有效降低可能需要使用到的用地範圍，因此設計一個同地點位於兩個深度的假想地下處置設施，進行岩石力學與熱學的耦合分析，評估可能造成的影響。

   近場的研究結果顯示，在選定的環境條件下，即使處置設施在同地點不同深度下進行開挖，對於岩體造成的破壞也僅只在表面，開挖過程仍可維持穩定，熱應力在設施周圍造成的破壞也有限。遠場的分析則運跑封閉後不同時間下溫度場的變化，並發現在廢棄物罐放置 3000 年後，地表可能出現 0.33 公尺的抬升，影響範圍可達處置設施周圍 1,600 公尺遠。

2. 注水導致斷層地震活動之多相流與地球化學耦合模式 (Coupled multiphase flow and geomechanical modeling of injection-induced seismicity on the basement fault., ARMA18-1114, 圖 4)

台電公司近幾年積極参與國際的研合作究計畫，自 2016 年 1 月起加入熱力-水力-力學-化學耦合大型國際合作計畫「DECOVALEX-2019」，目前執行中的 Task B 主要使用瑞士 Mont Terri 地下實驗室的實驗結果，探討粘土岩中，因水壓力增加，導致裂隙或斷層的力學變形，而產生再活化之現象。

本項研究為美國桑迪亞國家實驗室(Sandia National Laboratories，SNL)所執行，當大量流體以高壓注入地底，會造成孔隙壓力的增加進而影響區域的應力場分布。若是將二氧化碳注入地下含水層封存，則可能會產生包含液體與氣體的多相流系統，在這樣的環境條件下，增加的孔隙壓力很可能誘發斷層的活動而產生地震。瞭解相關的物理機制，並分析評估多相流受地震造成斷層透水性變化的影響，是本研究的主要目標，相關研究成果可與 DECOVALEX 的計畫執行團隊分享討論。

分析結果顯示，在注入井附近的二氧化碳飽和帶，會因為流動性高的二氧化碳而降低壓力的形成。低透水性的封閉斷層則成為一個水力與毛細管帶可阻擋液相的屏障，此封閉斷層的毛細管帶顯著增加了液相的壓力，滲漏的二氧化碳被驅動穿過儲集層與斷層間的介面。

3. 利用 PFC 顆粒模式模擬與時間相關之脆性岩體破壞 (Modeling Time-dependent Failure of Brittle Rock using PFC Grain-Based Model., ARMA18-236, 圖 5)

PFC 為 Particle Flow Code 的縮寫，為一離散元素分析程式，相

關理論由 Peter Cundall 在 1971 年所發展，根據顆粒力學的原理與牛頓運動定律計算力的平衡、位移量等，相較於傳統的連體力學數值方法，具有允許元素間有限度的位移及旋轉且分離的特性，運算過程可分析顆粒的接觸與分離。離散元素法(Discrete Element Method, DEM)在岩石力學領域的應用則包括邊坡破壞與土石流顆粒受壓影響、土壤力學與岩石力學實驗室試驗的模擬，以及岩體破裂行為等分析。

本研究即使用 PFC 的 GBM(Grain-based)模式，嘗試提出新的方法，用以模擬脆性岩石隨時間變化的破壞行為。宏觀來看，脆性岩石隨時間變化的變形行為，可以被視為一種結合兩種效應的結果，包括發生在顆粒內部以及顆粒邊緣的應力所造成的腐蝕。研究結果顯示，這個方法可以同時反應脆性岩石壁面的短期與長期力學強度。

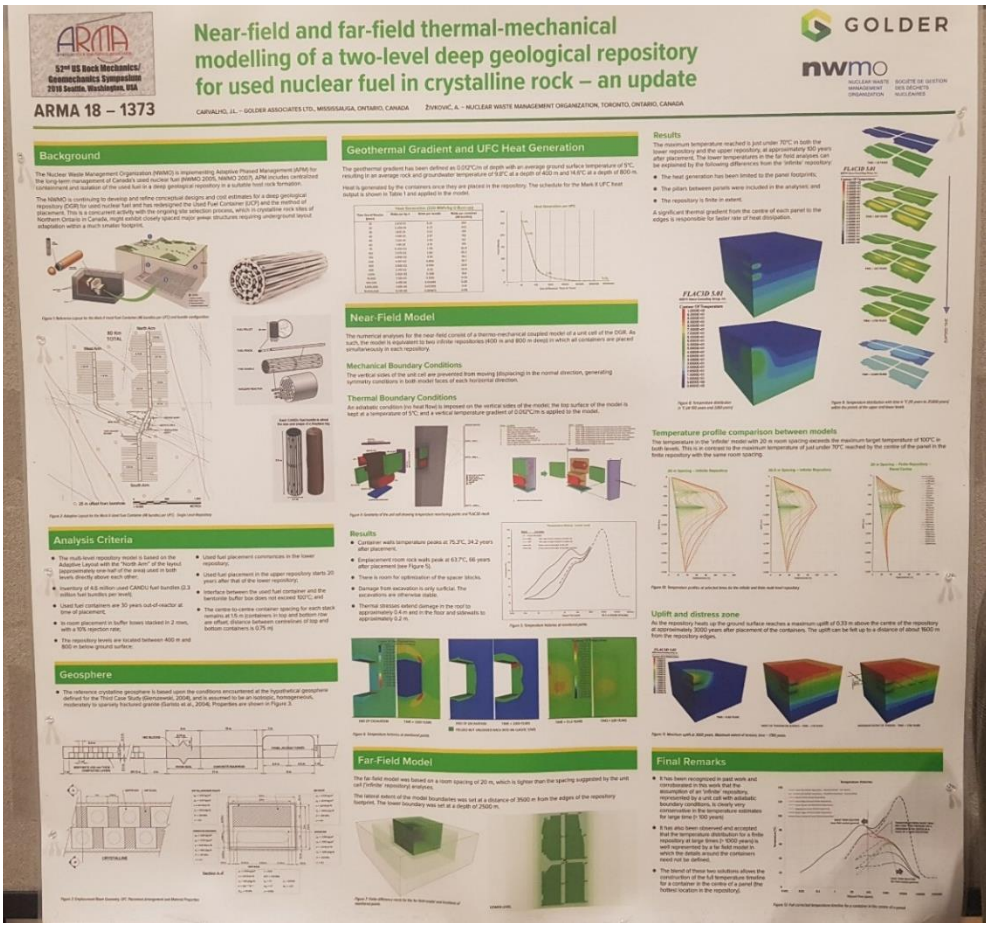


圖 3 ：加拿大假想處置設施評估(ARMA18-1873)

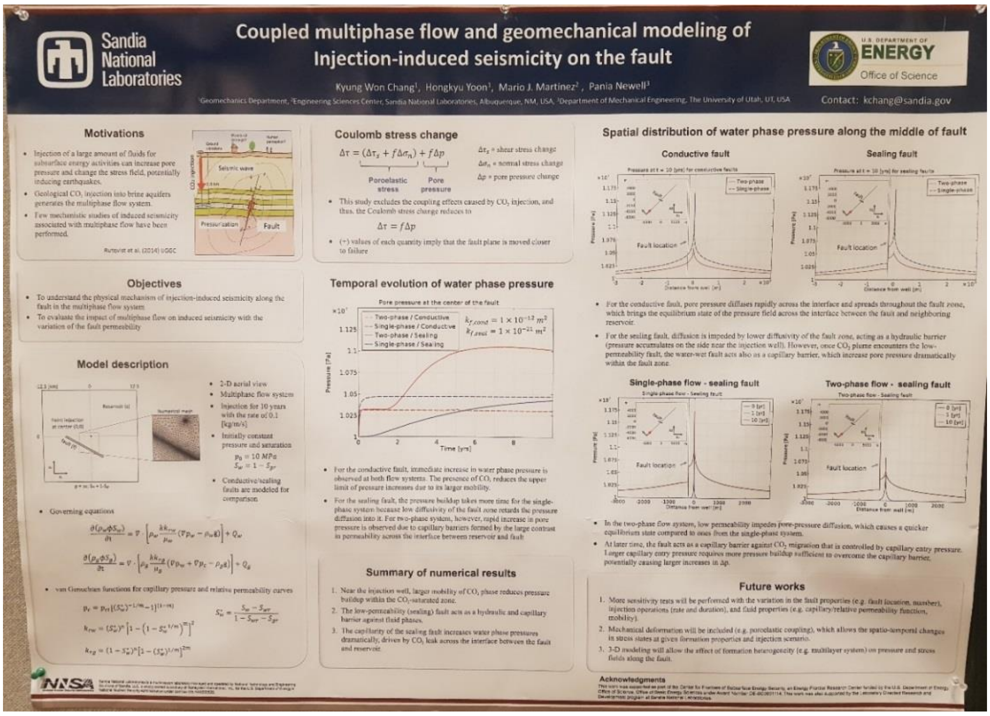


圖 4 ：注水導致裂隙再活化研究(ARMA18-1114)

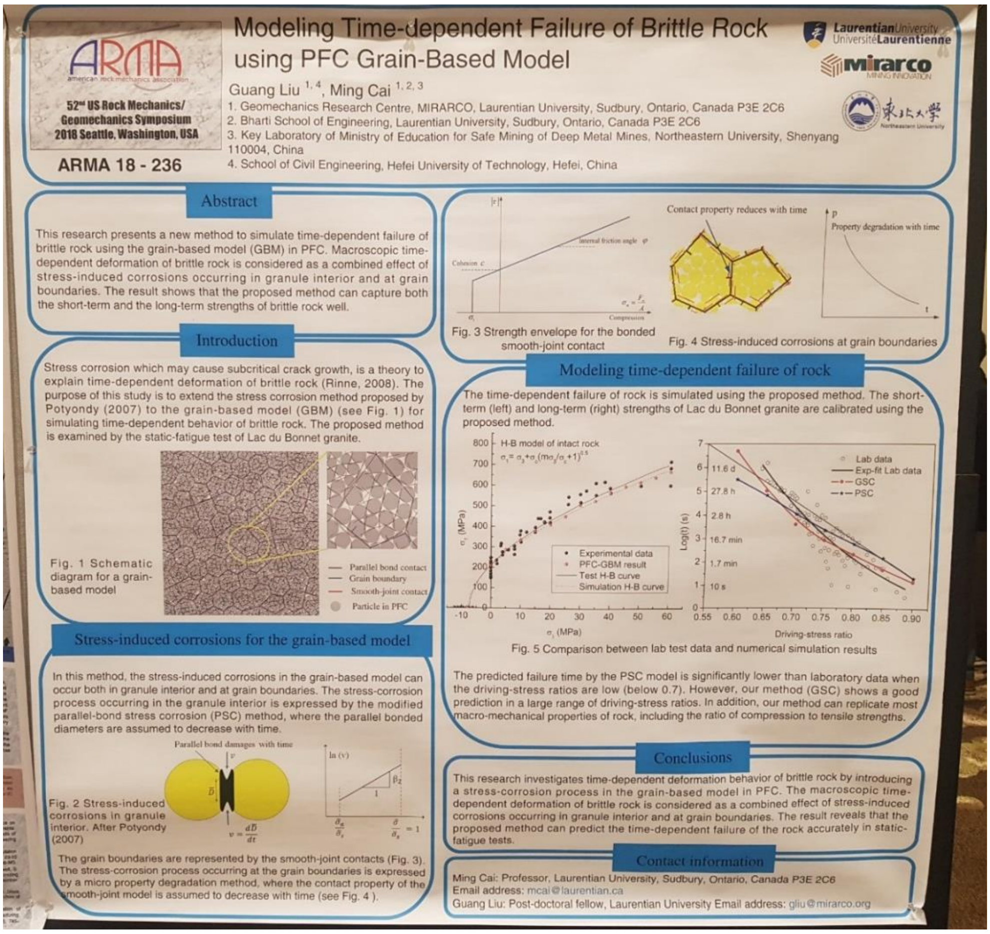


圖 5 ：結合 PFC-GBM 法評估脆性岩破裂行為(ARMA18-236)

（二）調查技術與試驗

在處置隧道的配置設計上，現地應力之大小是影響隧道安全性的主要因素，處置隧道開挖過程中，隧道周圍的岩體應力狀態也可能影響隧道發生變形行為或水力特性，因此相關調查技術與試驗方式都是目前研究的重要方向：

1. 基於取芯過程井孔側壁彈性變形與應力釋放的新應力量測方法 (A New Method of Stress Measurement Based on Elastic Deformation of Sidewall-Core with Stress Relief during Coring., ARMA18-672, 圖 6)

   現地量測岩石應力的方法主要包括直接量測(水力破裂、套鑽法等)、間接量測(岩心非彈性應變回復法、音射法、岩心直徑試驗法等)以及利用地質構造古應力反演的方法來推估，本研究則為日本東北大學 ITO Takatoshi 教授所提出推估應力的新方法。現地應力的調查為我國用過核子燃料最終處置計畫現階段的重點發展項目之一，與 Takatoshi 教授的交流過程中互相交換了對於現地應力調查技術的看法，未來期能有合作的機會，持續精進目前計畫執行團隊的技術能力。

   由於傳統的岩心直徑試驗法(Diametrical Core Deformation Analysis, DCDA)無法直接判定每個應力單元分量的強度，但若在礦坑或是隧道內有機會再進行鑽孔，則有可能裡用至少在三口鑽井內的三個不同方向所得到的三維現地應力來進行絕對強度的判定。即使只有單口井的情況下，也可以利用旋轉側壁取芯工具來達到相似的條件，輔以原本的鑽井建構三維的現地應力強度。

   本研究為建立現地應力與孔內側壁岩芯變形的關係式，於室內實驗室使用一具有水平向鑽孔的樣本，讓樣本處於受到單軸壓縮狀態，於垂直向鑽取樣本側壁的岩芯進行試驗。分別比較垂直側壁岩芯軸向上的平面其觀測值與理論值的應力差異，結果顯示，岩心直徑試驗法

所判定的應力差異大致上與理論值相符，表示靠近鑽孔周圍應力集中的徑向變化可以利用側壁與岩心直徑試驗法來推估，此一新方法可有效利用岩心直徑試驗法來判定現地應力的絕對強度。

2. 井孔拉破破壞過程的音射監測 (Acoustic Emission during Borehole Breakout., ARMA-619, 圖 7)

本研究為美國桑迪亞國家實驗室(Sandia National Laboratories，SNL)的 R. Choens 等人所執行，主要利用花崗岩樣本，結合音射(Acoustic emission)的監測進行井孔內拉破破壞(breakout)的實驗與模擬。實驗結果顯示，有效應力與應力路徑控制了拉破破壞的生成以及井孔內破壞的累積，並驗證了有效應力定律可應用在井孔的變形。比較音射行為在不同孔隙水壓實驗條件下的結果，顯示拉破破壞的發展會在應力峰值發生之前，並持續進一步對地層造成破壞，並產生剪力破裂。

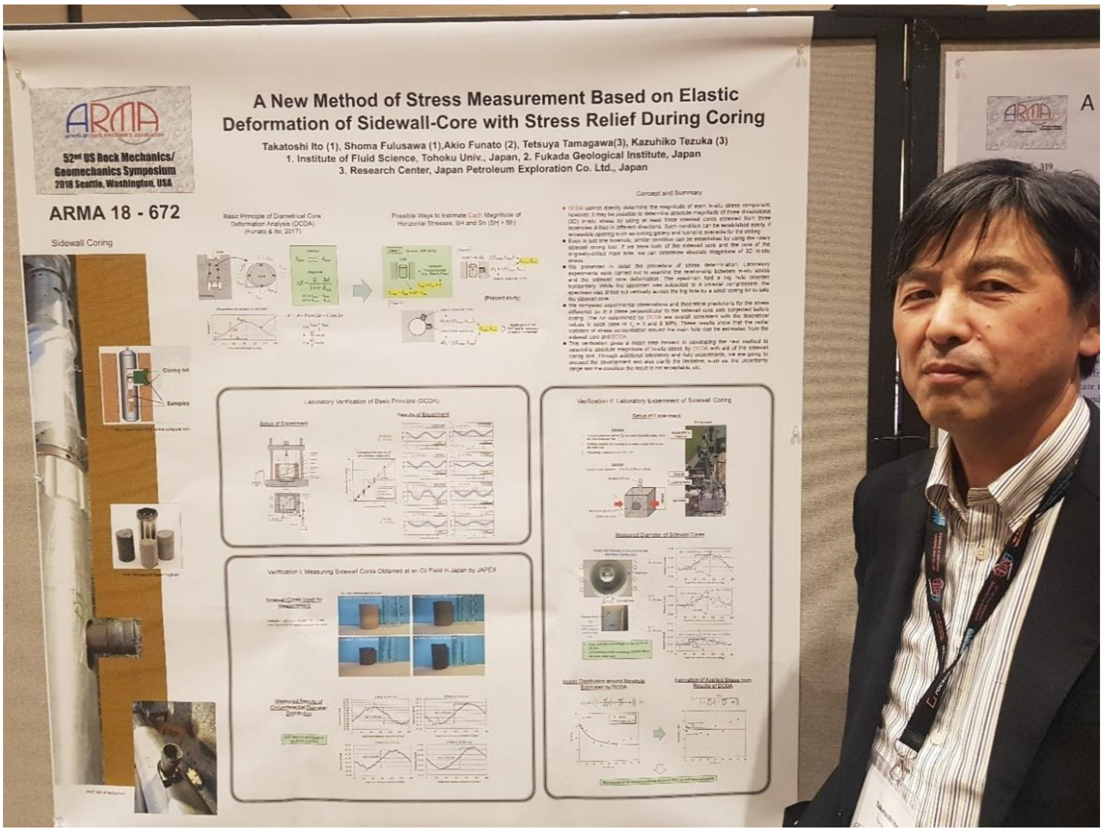


圖 6 ：使用岩心直徑試驗法評估現地應力(ARMA18-672)

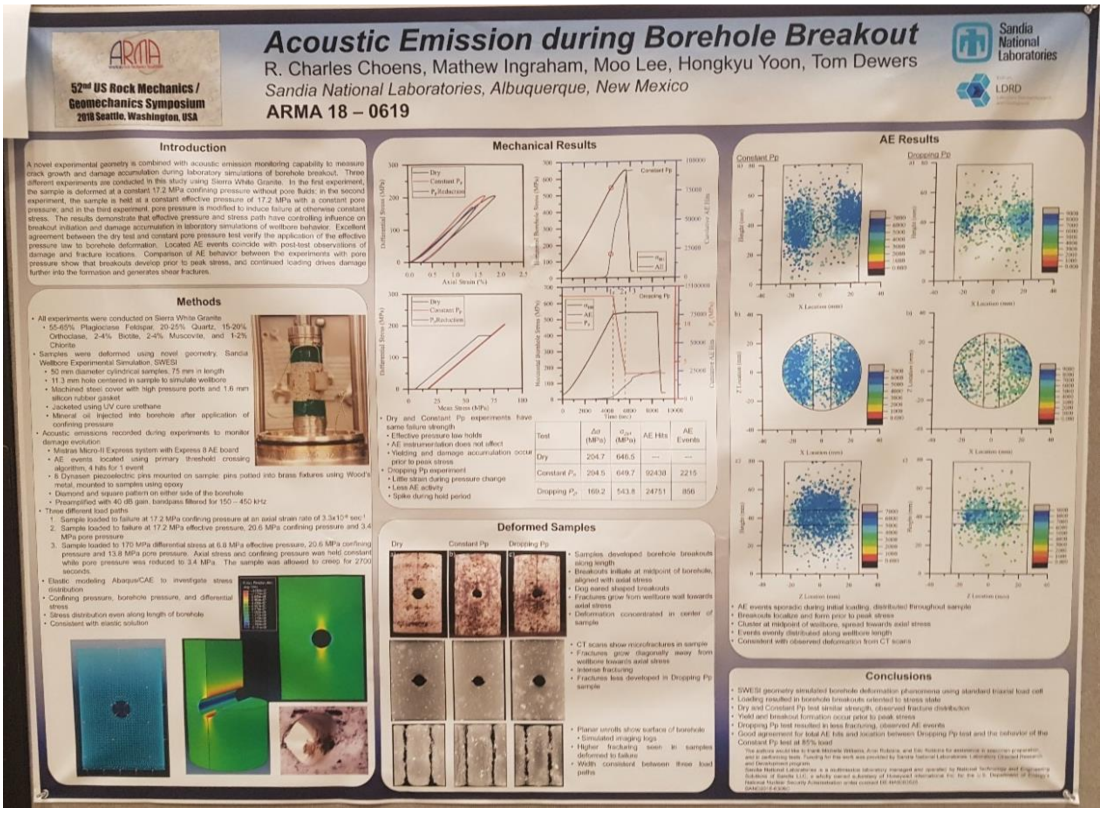


圖 7 ：井孔拉破破壞過成的音射監測(ARMA18-619)

（三）其他議題

1. 虛擬實境在岩石工程的應用 (Applications of virtual and mixed reality in rock engineering., ARMA18-798, 圖 8)

虛擬實境(virtual reality，VR)技術為近年所發展的電腦科技，利用電腦模擬提供視覺上的三維空間的擬真情境，隨著技術的演進，相關應用已逐步擴展到不同領域，本次會議現場即有工程顧問公司展示最新的虛擬實境軟體，可提供使用者進行空間測繪、土木結構動力分析模擬、以及互動式的建物設計功能等，也有如本項研究開發在岩石工程上的應用技術，包括邊坡破壞的虛擬實境、三維地質資訊的圖資測繪、結合衛星影像與雷達測高等綜合資訊、岩芯的全息影像等。

由於處置相關工作涉及公眾議題，場址的合適性調查必須整合許多不同地質領域的資料，因此資料的視覺化與場址描述模型的建立是相當重要的工作，虛擬實境以及擴增實境(Augmented Reality, AR)的應用對於處置計畫的研究與溝通工作將有一定的助益，未來將持續關注相關技術的發展，嘗試將虛擬實境技術與處置設施的相關研究進行結合。

2. 增強型地熱地下實驗室計畫 Collab 相關研究

美國南達科他州(South Dakota)的 Homestake 金礦過去曾是美國境內主要的金礦區，停止開採關閉後即逐漸停止維護，但過去所挖掘的採礦坑道則成為可供深地層相關研究的一個實驗設施(Sanford Underground Research Facility, SURF)。2017 年開始，美國能源部(Department of Energy, DOE)下的地熱科技辦公室(Geothermal Technologies Office, GTO)出資成立一個大型的增強型地熱(Enhanced Geothermal Systems, EGS)研究計畫 Collab，即選定這個地下礦坑進行

地熱相關的現地調查與研究，由於一般增強型地熱所需要的深度達一千公尺以上，相關試驗與調查的成本極高，利用廢棄礦坑的方式可有效降低費用，並以具有過去所累積豐富的場址特性資料。

由於用國核子燃料採深地層最終處置已是國際間的共識，為確認國內深層地質環境，發展我國自有的深層調查技術，並提供一個展示與技術驗證平台供外界討論與進行溝通，地下實驗室的建立也有相當的必要性。會議中，與美國勞倫斯伯克利國家實驗室(Lawrence Berkeley National Laboratory)的 Craig Ulrich 有相當深度的交流討論(圖 9)，分享利用廢棄礦坑作為地下實驗室的推動經驗與最新研究進展，由於增強型地熱主要也是針對裂隙岩體的地下水流、水質化學特性等特徵進行研究，相關試驗規劃與技術發展非常值得我國處置計畫借鏡。有關增強型地熱相關發表論文羅列如下：

- EGS Collab Project: Stimulation and Simulation (ARMA18-1345)
- Natural Fractures and Their Relationship to the EGS Collab Project in the Underground of the Sanford Underground Research Facility (SURF). (ARMA-1190)
- The distribution, orientation, and characteristics of natural fractures for Experiment 1 of the EGS Collab Project, Sanford Underground Research Facility. (ARMA18-1252)
- Hydraulic Fracture Modeling in Support of EGS Collab Treatment Designs. (ARMA18-862)

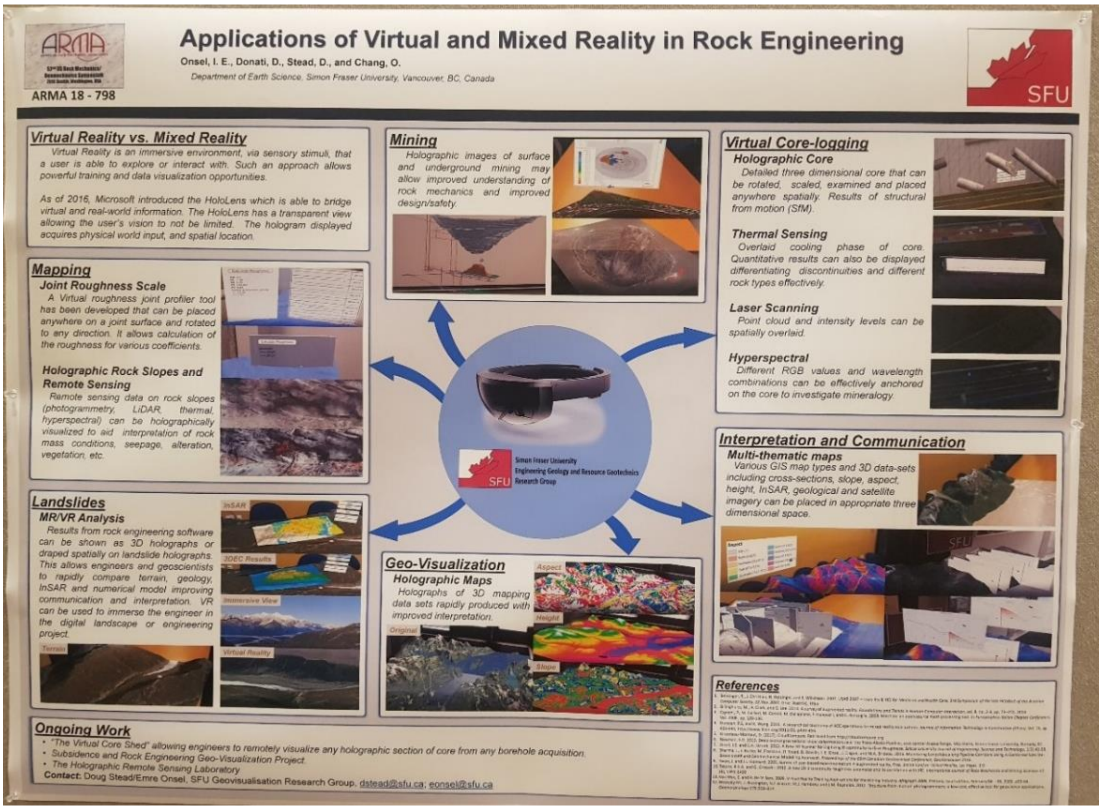


圖 8 ：虛擬實境在岩石工程的應用(ARMA18-798)

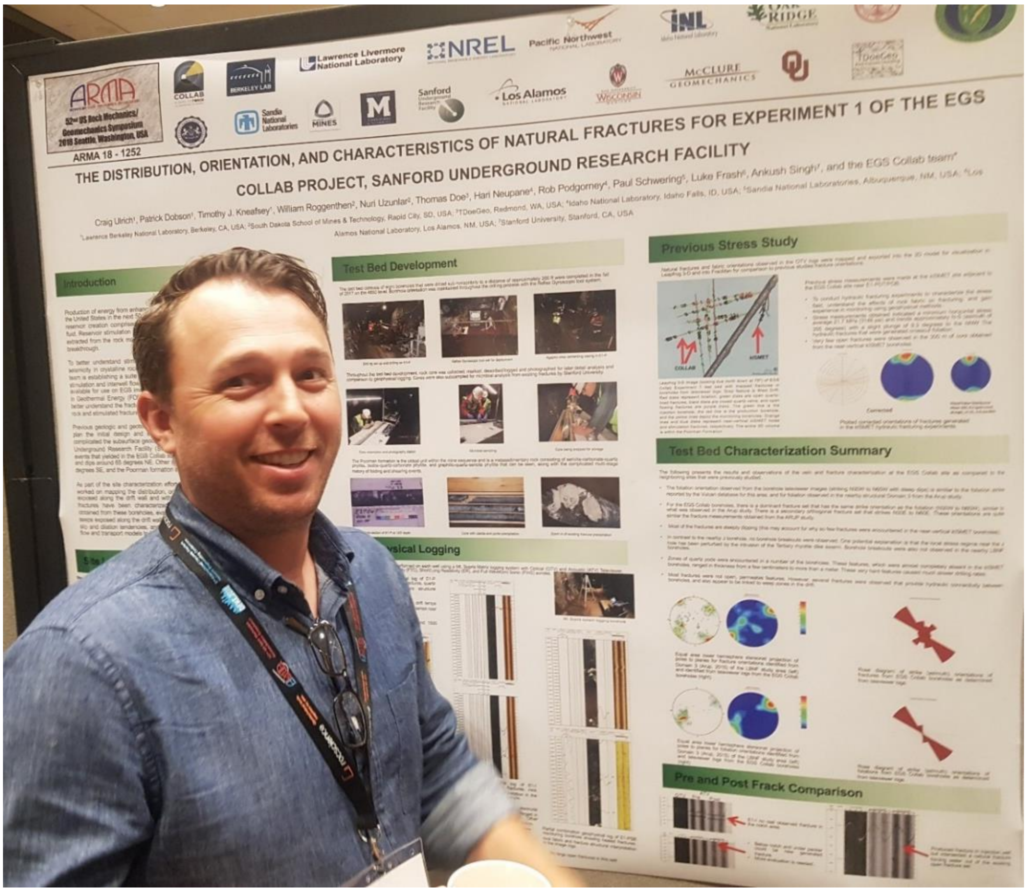


圖 9 ：增強型地熱研究(ARMA18-1252)

二、第 2 屆離散裂隙網路工程研討會

本研討會為第 2 次舉辦，第 1 屆研討會於 2014 年 10 月 19 至 22 日在加拿大溫哥華召開，主辦單位為加拿大岩石力學學會(Canadian Rock Mechanics Association, CARMA)，會議就 DFN 技術發展、應用及特性進行科學探討；本屆主辦單位為美國岩石力學學會，廣泛邀請學術界、產業界、顧問公司及政府部門等相關專家，發表目前 DFN 模擬技術與應用成果，並提出模式精進與建議，會議主軸包括：(1) DFN 理論與基礎；(2)DFN 應用於基礎設施與地質災害的之方法；(3)DFN 應用於地下及地表開礦之方法；(4)石油、天然氣與地熱能；及(5)放射性廢棄物的管理等。大會議程詳見附錄 II，本屆會議共發表 114 篇論文，口頭報告 94 篇；海報發表 20 篇，論文發表主題如 表 2，會議過程摘述如下：

表 2：DFNE 論文發表主題與論文數

會議主軸	論文分類	發表論文數
DFN 理論及基礎	DFN 岩體模擬	5
	裂隙介質中波傳行為	4
	DFN 計算方法的改善	5
	地表及地下開礦的穩定性	8
	DFN 耦合模式	10
	DFN 水流模型	8
DFN 應用於基礎設施與地質災害的之方法	以現地資料建構 DFN 模型	12
	DFN 在邊坡及隧道工程之應用	6
	岩體的有效參數	5
DFN 應用於地下及地表開礦之方法	水力破裂的進階應用	11
	水力破裂與動態應力	6
石油、天然氣與地熱能	地熱及地下水化學模擬	6
放射性廢棄物的管理	場址特性與確認	7
	溶質傳輸與安全評估	7
	地下水流與核種傳輸	6
	儲存庫的 DFN 案例研究	8

（一）開幕式暨專題演講

本屆大會主席為 Geofractal 專業顧問公司董事的 Bill Dershowitz 博士，Bill Dershowitz 博士過去在 Golder 公司擔任技術總監，為 FracMan 軟體技術開發團隊的創始人，專長為岩石力學及地下水動態模式，在地下水的熱及溶質傳輸、坑道穩定性、水力破裂、裂隙儲集、地質力學、地熱資源等專業領域方面有近 40 年的開發經驗，在進行簡單開幕致詞後，開始進行專題演講，專題演講的內容摘述如下：

1. 首先由任職於法國國家科學研究中心(Centre National de la Recherche Scientifique, CNRS)的 Phiplippe Davy 博士分享 DFN 概念模式的應用經驗，DFN 概念模式係指將現地的裂隙調查、水文地質調查及地質特性調查等資料，透過數學模式將其整合成一可作為分析使用之模型，該模型包括有：(1)現地調查資料；(2)經驗與知識；(3)DFN 概念模式；(4)離散或連續體模式及(5)模型預測與應用等 5 個面向(如圖 10)，透過資料的統計分析，整合各項現場調查成果並將其最佳化，以供不同領域應用及分析。在進行 DFN 概念模式應用時，應注意模式的假設前提(如圖 11)，包括有：
   (1) 在 DFN 的模擬中，尺度規模是一個重要的議題，應注意不同尺度下裂隙參數的差異性，在不同尺度下，裂隙尺寸與裂隙強度未必符合冪函數分布(Power Law distribution)的關係。
   (2) 過去的經驗、知識、理論、驗證等都可以作為概念模式的開發基礎，但在模式的應用上，但仍要考慮不同尺度下理論與資料的適用性。
   (3) DFN 模式是一種受到內營力(如：收縮解理、解壓解理等)及外營力(如：擠壓破裂、斷層破裂、摺皺等)作用控制，而隨機產生的裂隙模式。

(4) 僅靠校正(calibration)DFN 模式是不夠的，還須要透過與現地調查資料的確認(Validation)才能確定模式的適用性。

2. 接下來由英屬哥倫比亞大學礦業工程研究所(the University of British Columbia, Institute of Mining Engineer)的 Davide Elmo 副教授說明，從現地調查資料到建構 DFN 模式並應用於模擬的過程中的不確定性(圖 12)，這些不確定性包括：

(1) 地質構造不確定性：現地調查資料特徵化時產生的不確定性；

(2) 參數分析不確定性：地質參數分析時產生的不確定性，包括參數的空間差異與升尺度的不確定性；

(3) 模型不確定性：現地調查資料應用於理論模型時產生的不確定性；

(4) 人為不確定性：人為量測誤差或專業判斷時主觀認知的不同所產生之誤差。

上述的不確定性，會透過逐漸累積的資料、經驗及知識而逐漸降低，並透過持續增加的現地資料與模式分析間不斷的迭代過程，進行交互驗證與確認，以增進其信心指標。

3. 最後一場專題主講人為由 Golder 公司的水文地質專家 Lee Hartley 博士，他以瑞典及芬蘭將 DFN 模式應用於用過核子燃料最終處置場的安全評估為例，說明其適用性及可行性。其應用流程如下：

(1) 利用現地調查資料(地表地質調查、地球物理調查及鑽探等)，建立區域地質概念模型(Geological Conceptual Model)及離散裂隙網路參數集(DFN Recipe)，作為場址描述模型(Site Descriptive Model, SDM)的基礎(圖 13)。

(2) 以地質概念模型、水文地質模型及離散裂隙網路參數集，建構三

維離散裂隙網路模型(3D DFN Model)，並進行地下水流場分析與模擬。

(3) 依前項地下水流場分析結果，套入放射性核種及粒子傳輸模型，進行核種外釋的模擬、分析及評估，以瞭解從近場、遠場及生物圈的傳輸過程中劑量影響的範圍(圖 14)。

(4) 透過不斷的迭代過程，並與現地資料進行確認，逐步降低其不確定性，並將安全分析報告及安全論證作為申請建造執照的必要文件，以證明有能力確保處置場的長期安全。

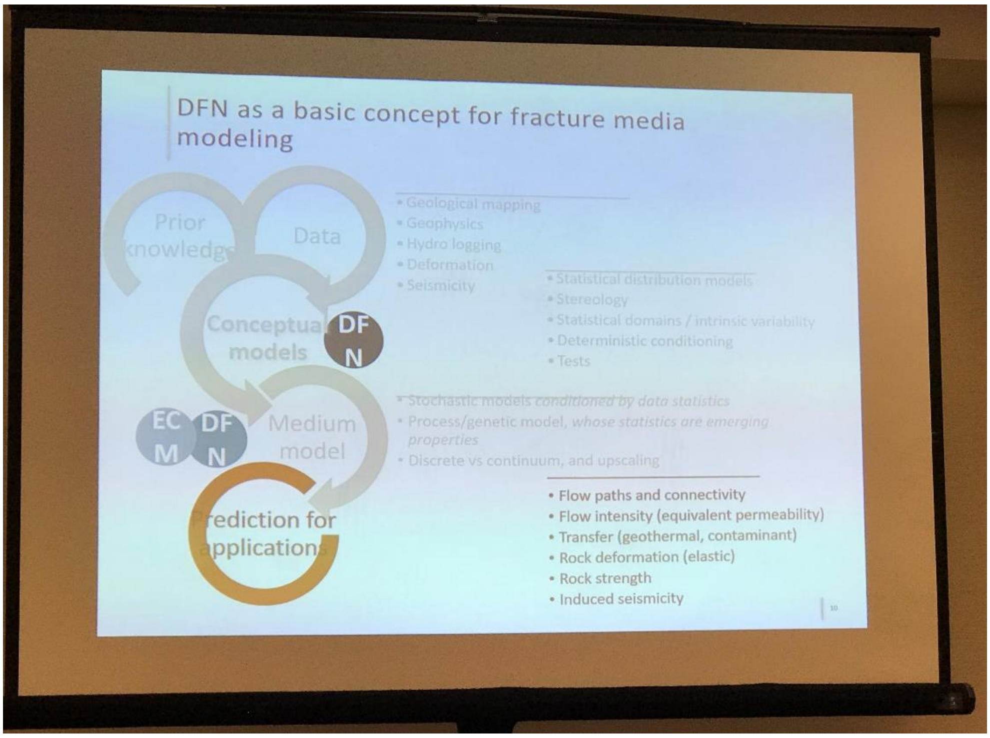


圖 10 ：DFN 模式包含的內容

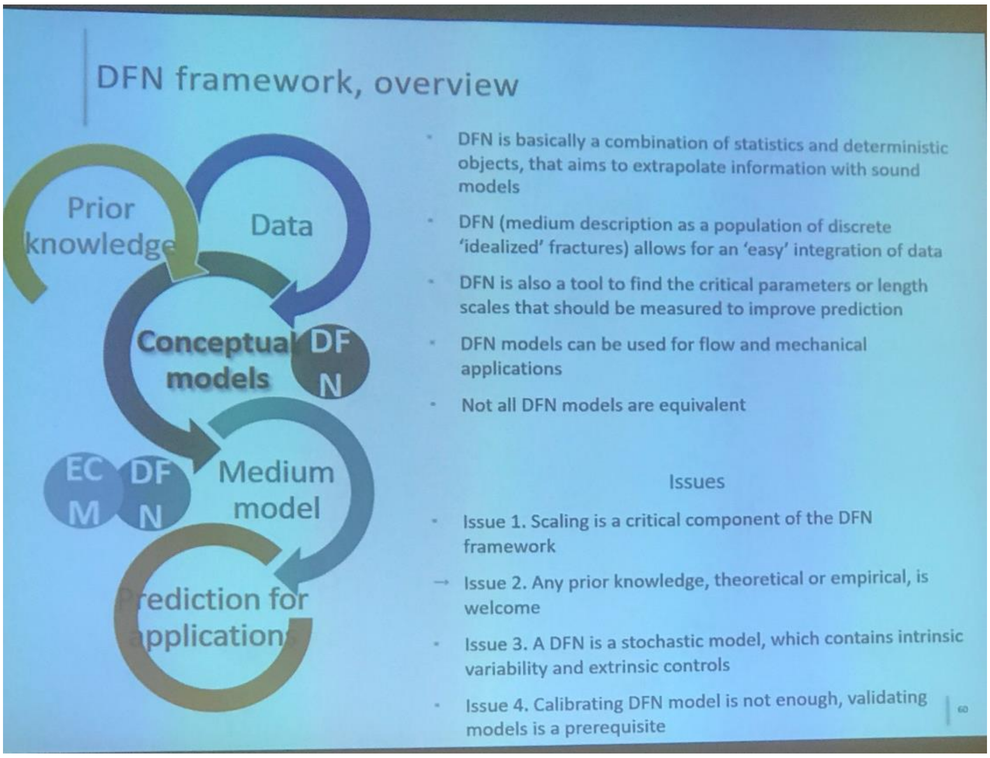


圖 11 ：應用 DFN 模式應注意的假設前提

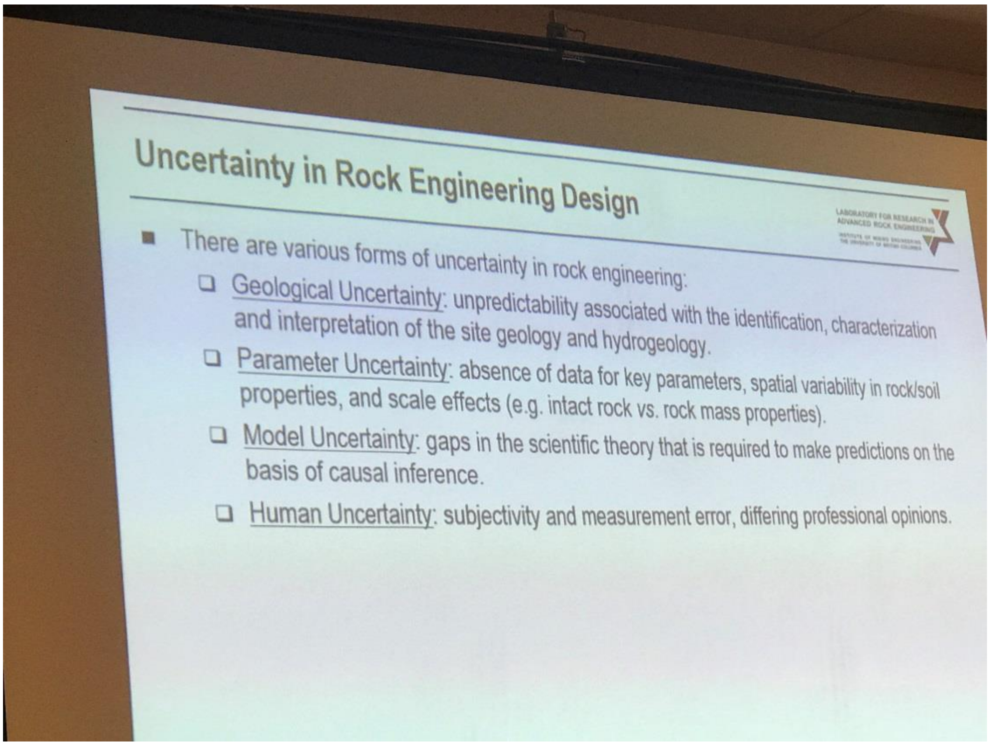


圖 12 ：岩石工程設計時的不確定性

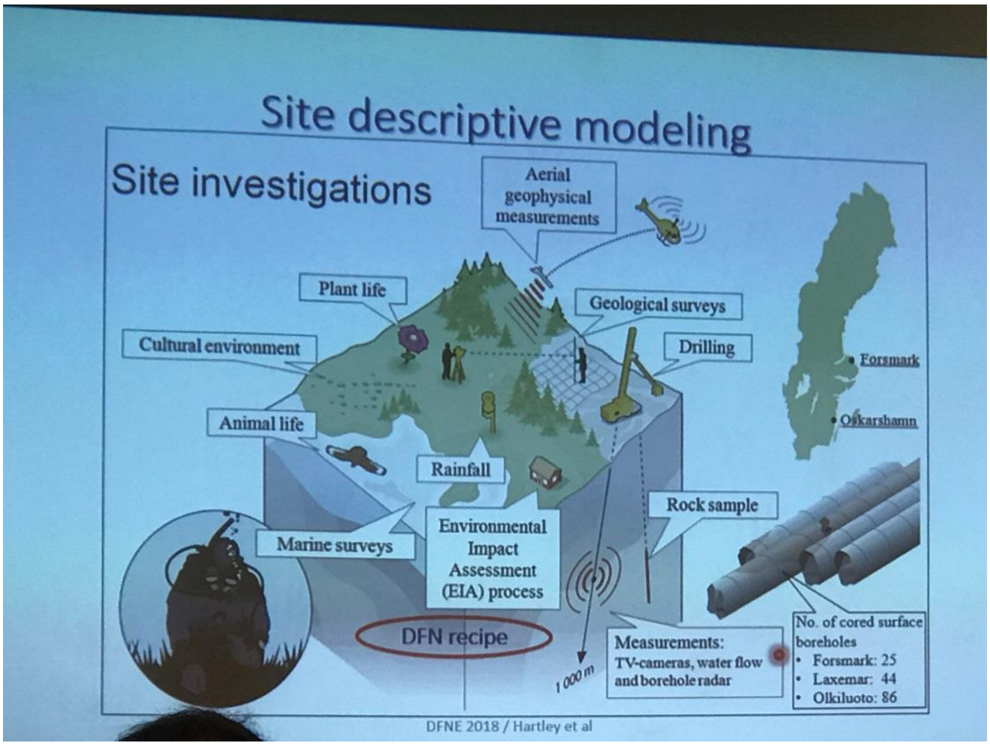


圖 13 ：場址描述模型

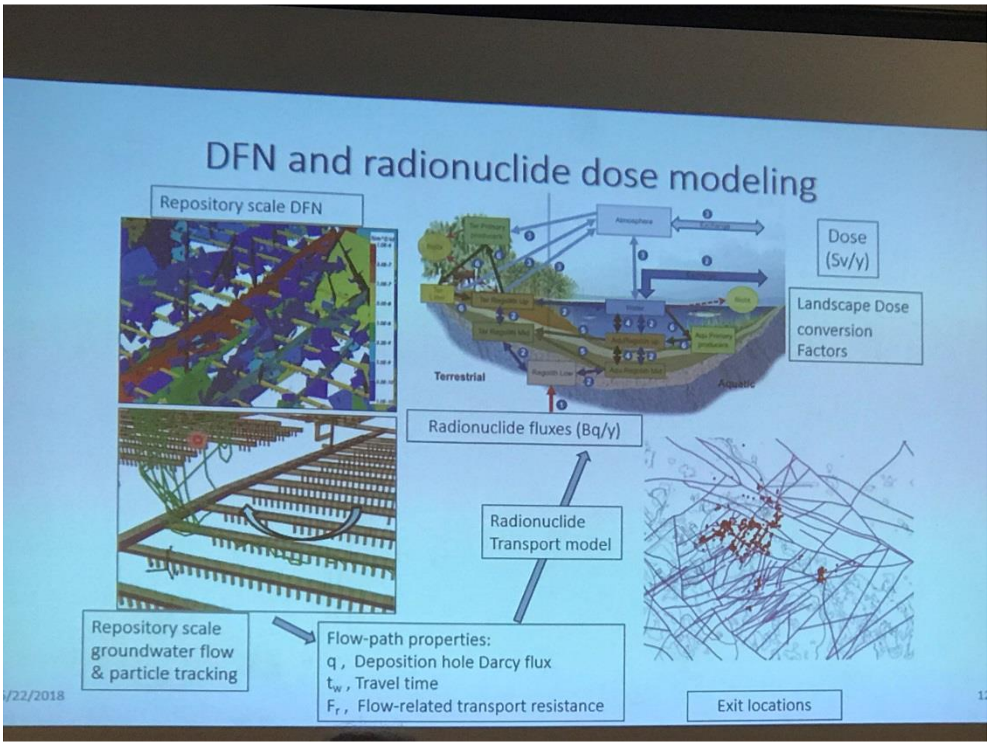


圖 14 ：以 DFN 模型評估質點傳輸途徑

（二）技術論文發表

因多項技術議題同時進行論文發表，僅就與放射性最終處置相關技術議題報告內容，重點摘述如下：

1. 溶質傳輸與安全評估

國際間目前多採用深層地質處置及多重障壁 2 種概念來進行高放射性廢棄物的最終處置設計，透過厚層的岩層將將放射性廢棄物隔離人類生活圈，並以人工及天然障壁組成多重障壁系統，將放射性核種圍阻於障壁中，即便放射性核種外釋，亦可透過障壁系統遲滯其外釋速率，待其傳輸至生物圈時，輻射劑量已降低至對生物無害之等級，而目前的理論模式，水為放射性核種的唯一傳輸媒介，放射性核種可透過溶解於地下水中以離子的方式擴散或傳輸，也可以質點的方式隨著地下水流動遷徙，本項技術探討核種以溶質傳輸方法進行外釋的評估，並進行相關的安全評估分析，相關技術報告內容摘述如下：

(1) 首先由 Wood 工程服務公司 Mosley 工程師，以芬蘭 Olkiluoto 最終處置場為案例，說明更新後的 SDM 及其應用結果(圖 15)，並以更新後的 SDM 獲得主管機關審查同意並發放處置場的建造執照，更新後的 SDM 能以更適切的量化標準，描述場址的地質、水文地質、地球化學及力學特性，並以 DFN 結合地質與水文地質，以迭代方式評估以不同方法及尺度下取得之現地資料，將 DFN 模擬結果與實測資料進行校正與不確定性分析(圖 16)，以提升模式的可信度。

(2) 接下來由 NWMO 的 Jianming Chen 博士以「如何在結晶岩深層地質處置設施封閉後安全評估決定最重要的井孔位置」為題，說明加拿大最終處置場的研究進展，加拿大目前仍處於場址評選階段，就國內 22 個候選場址進行現地調查與安全評估(圖 17)，目前正

在 Ignace 地區進行現地鑽探，以進行該候選場址後續的安全評估工作。報告以一假想的結晶岩場址，進行封閉後安全評估模擬，並以一假設情節：未被評估到的廢棄物罐破裂且放射性核種大量釋出，而不知情的人類鑽取水井，藉以評估該行為可能受到的最大影響。首先以質點追蹤法評估放射性核種外釋的影響範圍，再分析不同的水井位置及質點傳輸軌跡的相關性(圖 18)，計算各水井的放射性劑量的最大峰值及可能的放射性核種(圖 19)，以瞭解廢棄物罐配置區域的風險值。評估結果於 12,000 至 56,000 年後劑量達到最高峰值，劑量貢獻最大的核種為碘 129。

(3) 後續由核能研究所的黃鈺翔工程師以 SNFD2017 報告中，廢棄物罐的腐蝕失效情節進行報告，並以安全評估模式鏈(Assessment Model Flowchart, AMF 圖 20))說明評估流程。腐蝕情節假設處置場於封閉後，地下水隨著時間逐漸經由岩體裂隙侵入處置設施，逐步侵蝕廢棄物罐周圍的緩衝材料，並開始腐蝕廢棄物罐，導致廢棄物罐失效而喪失圍阻功能，主要劑量貢獻核種為氯 36 及碘 129(圖 21)。

2. 地下水流與核種傳輸

本技術項目著重於評估放射性核種以質點傳輸的方式隨著地下水流動遷徙行為，要評估核種的傳輸途徑首要瞭解地下水的流場特性，而評估結晶岩的流場特性則須借重 DFN 技術，藉由分析連通的裂隙，以瞭解結晶岩體內的地下水流場分布與特性。

美國 Sandia 國家實驗室的 Elena Kalinina 高級研究員，參考熱力(Thermal)－水力(Hydrological)－力學(Mechanical)－化學(Chemical)耦合研究國際計畫 DEVOVALEX (DEvelopment of COupled models and their VALidation against EXperiments)分享的日本瑞浪花崗岩地下實驗室(Mizunami Underground Research Laboratory, MIU)周邊裂隙參數資料與水文地質參數 (圖 22)，進行地下水流的模式驗證研究。本研究以 FracMan 建立 DFN 模式，並產生裂隙的實現值，並使用該實驗室自行開發的開放軟體 PFlotran，建立地下水流場模擬 (圖 23)，透過模型預測值與與現場資料的比對，就模式的適用性進行驗證與確認。經比對模型分析之地下水滲流量與現場觀測值一致，顯示透過結合 FracMan 與 PFlotran 的研究方式，可有效的模擬現地的地下水流場，且具有相當高的可信度。

3. 場址特性與確認

經由現地調查資料建立的場址特性參數，可提供進行各項模式的分析與模擬，但模式的分析結果的正確性，仍須透過模式的驗證與現地資料的確認，國際原子能總署(International Atomic Energy Agency, IAEA)發布的放射性廢棄物地質處置設施特殊安全導則(Geological Disposal Facilities for Radioactive Waste, No. SSG-14)亦指出需透過驗證(Verification)、校準(Calibration)與確認(Validation)來建立評估的信心，相關技術報告內容摘述如下：

(1) 工業技術研究院的黃淞洋副研究員以臺灣東北部花崗岩體為例，運用現地參數量測及地質參數統計分析，搭配地表及孔內地質構造特徵量測，探討裂隙形成機制、裂隙應變趨勢及裂隙參數分布隨空間變化特性(圖 24)。根據地物井測資料解析結果顯示，地下岩體約以深度 296 m 為界，具有為一明顯的數值變化界線，推測上部岩體可能受到構造剪切作用較為強烈，造成淺部岩體裂隙發達及礦物變形量較大，導致電阻、自然加瑪值及聲波振幅較低。

孔內裂隙分布型態，亦約以深度 296 m 處為界，分為上下兩個區段：上部區段之裂隙在深度的分布上呈現為均勻分布，裂隙數量較多而密集，主要裂隙位態叢集之傾向與傾角為(347˚, 35˚)，次要裂隙叢集之傾向與傾角為(59˚, 30˚)；下部區段之裂隙數量較少，僅呈現局部區段的富集現象，裂隙主要發生在岩層的破碎帶。主要裂隙叢集之傾向與傾角為(336˚, 36˚)。花崗岩體內部充填方解石脈之導水裂隙，可分為(257˚, 58˚)及(341˚, 37˚)2 組位態叢集，其中平均位態為(257˚, 58˚)之導水裂隙群經由三軸應力推算結果，顯示具有較高的滑動及擴張趨勢。上述研究成果後續可提供建構裂隙網路模型與地下水流場所需之裂隙特性資訊，以預測岩體中地下水可能的傳輸路徑(圖 25)。

(2) 日本原子力規制委員會((Nuclear Regulation Authority, NRA)核燃料廢棄物安全技術管理官內田雅大博士(圖 26)，就 DFN 模型連通裂隙及場址尺度特徵化參數的驗證與確認方面，參考瑞典 SKB 的 SR-Site 報告(TR-11-01)經驗，建議一套系統性的評估流程(圖 27)，以不斷的模式迭代與調查參數的精進，以進一步檢測運用模式與現地調查數據的適用性，階段性的提昇模型的精確度，建議的階段流程如表 3

表 3：DFN 模式驗證與確認流程建議

項次	階段	目標
1	建立特徵化的標準	建立場址特徵計畫所需之場址特徵參數的調查方法
2	初步預測模型	提供初步預測結果及第 1 階段的功能測度值分析
3	特徵化資料的補充	提供第 2 階段預測模型的初步確認 依據前項的結果進行進一步的補充調查
4	更新預測模型	以第 3 階段的資料提供更新後的預測結果及功能測度值分析
5	確認實驗	取得數據以確認方法的正確性
6	確認模型	取得功能測度值之參考值
7	評估	評估特徵化的標準及初步預測的極限 評估更新預測模型的極限 評估試驗與分析的數值 發展方法的驗證文件

(3) 中正大學劉台生教授以 SNFD2017 參考案例的離散裂隙網路參數集建立 DFN 模型及相關地下水流場與質點傳輸模擬(圖 28)。資料分析方面，地質鑽孔的裂隙資料可用以分類岩體區域及分析裂隙位態叢集，並利用地表及坑道的裂隙軌跡、大區域範圍內的線型構造，以冪函數分布描述裂隙尺寸分布。模擬結果以 10 組 DFN 實現值，透過擴尺度計算為 EPM 模式，以 Lawrence Berkeley 國家實驗室所開發的 TOUGH2 進行區域性地下水模擬(圖 29)。結果顯示黏滯度與地表高程重力為影響鹽水入滲的主要因素，且擴尺度後滲透係數的異質性亦增加地下水流場的複雜度；質點傳輸模擬結果顯示裂隙尺寸與裂隙的滲透係數之間存在正相關關係，大型裂隙往往係為重要的運輸路徑，若僅考慮平流項，則多組粒子群行進的軌跡都極為相近。

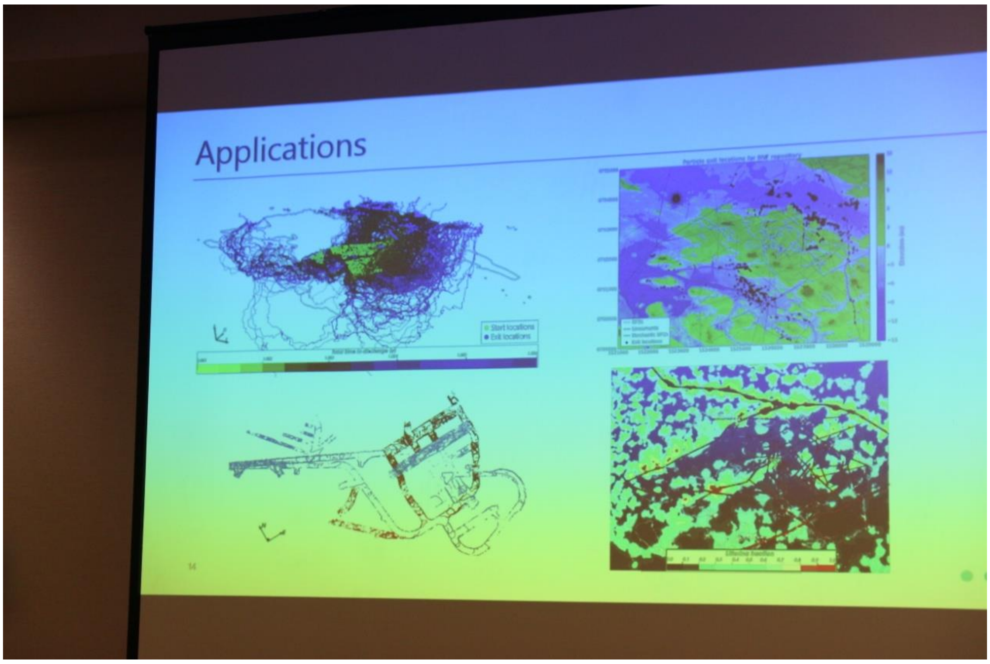


圖 15 ：SDM 的應用

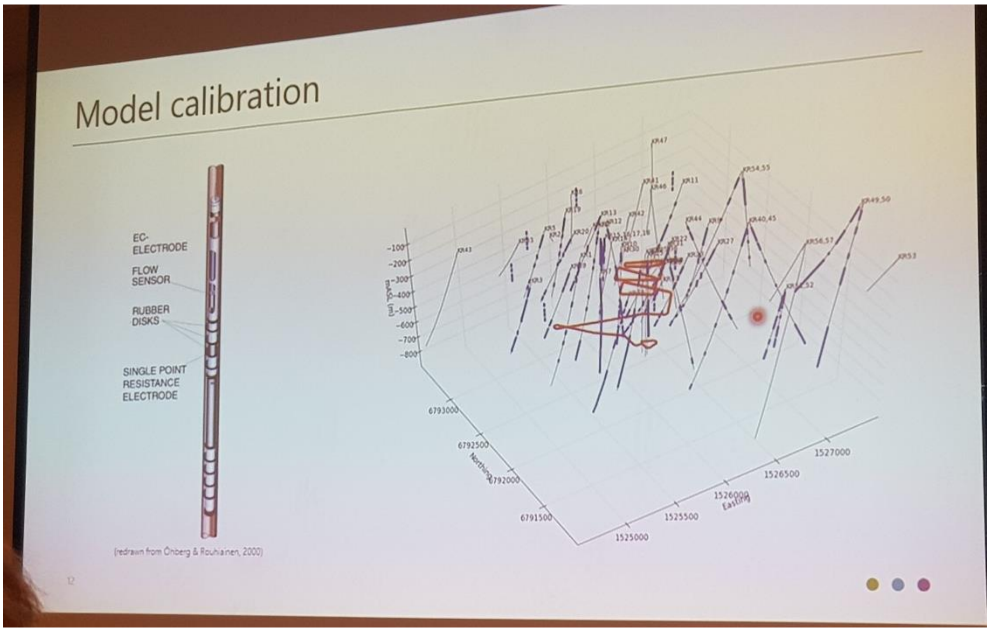


圖 16 ：模式的校準及確認

圖 17 ：加拿大高放候選場址分佈

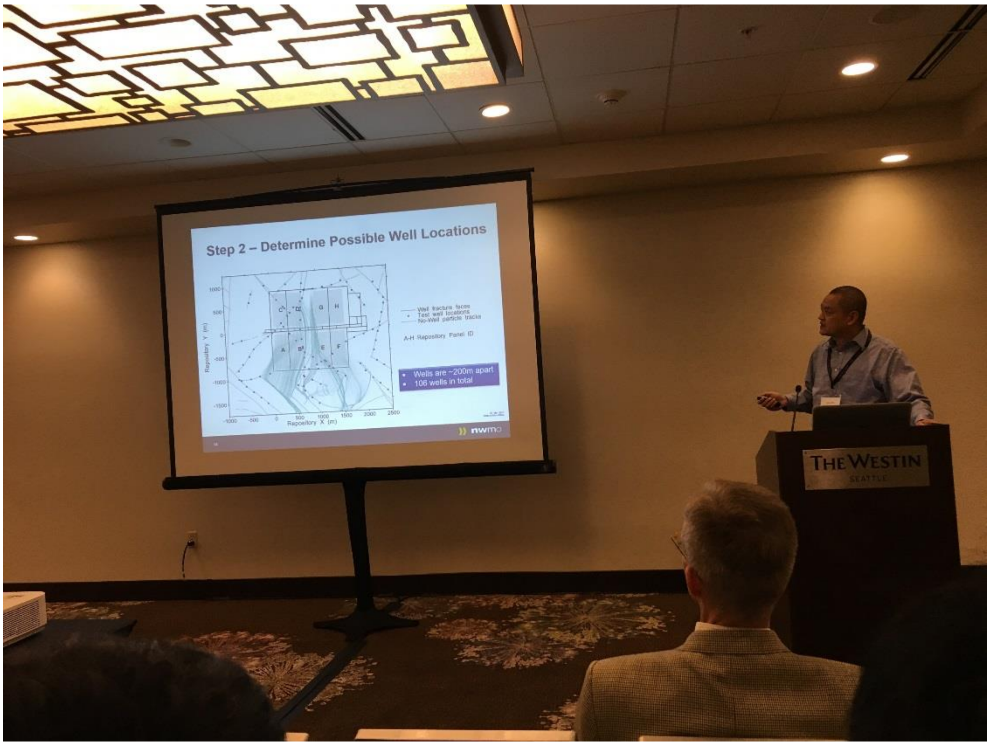


圖 18 ：質點傳輸軌跡與水井位置

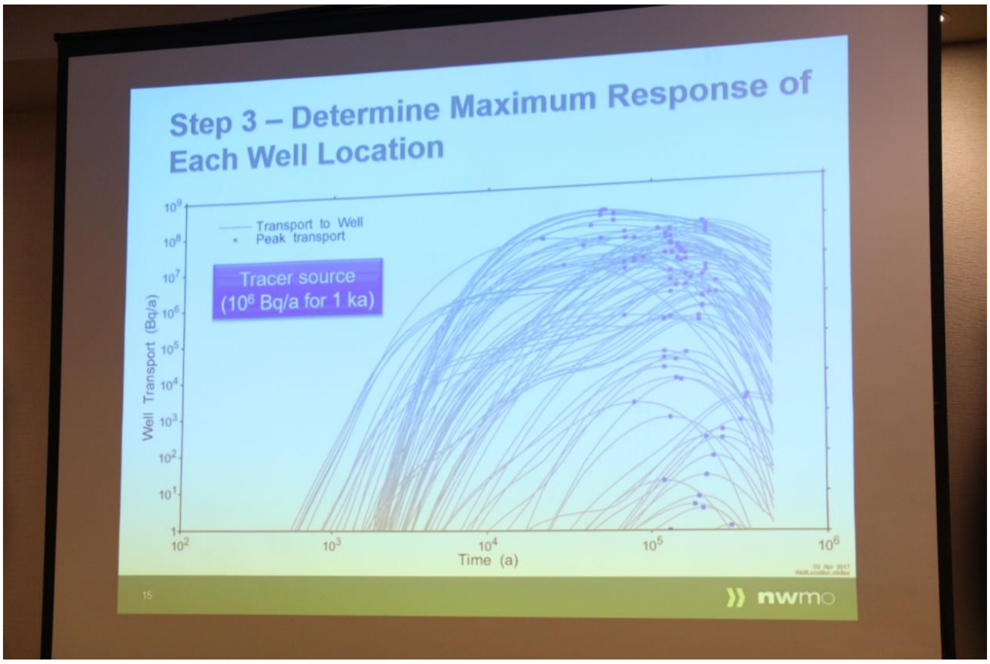


圖 19 ：各水井的最大劑量評估

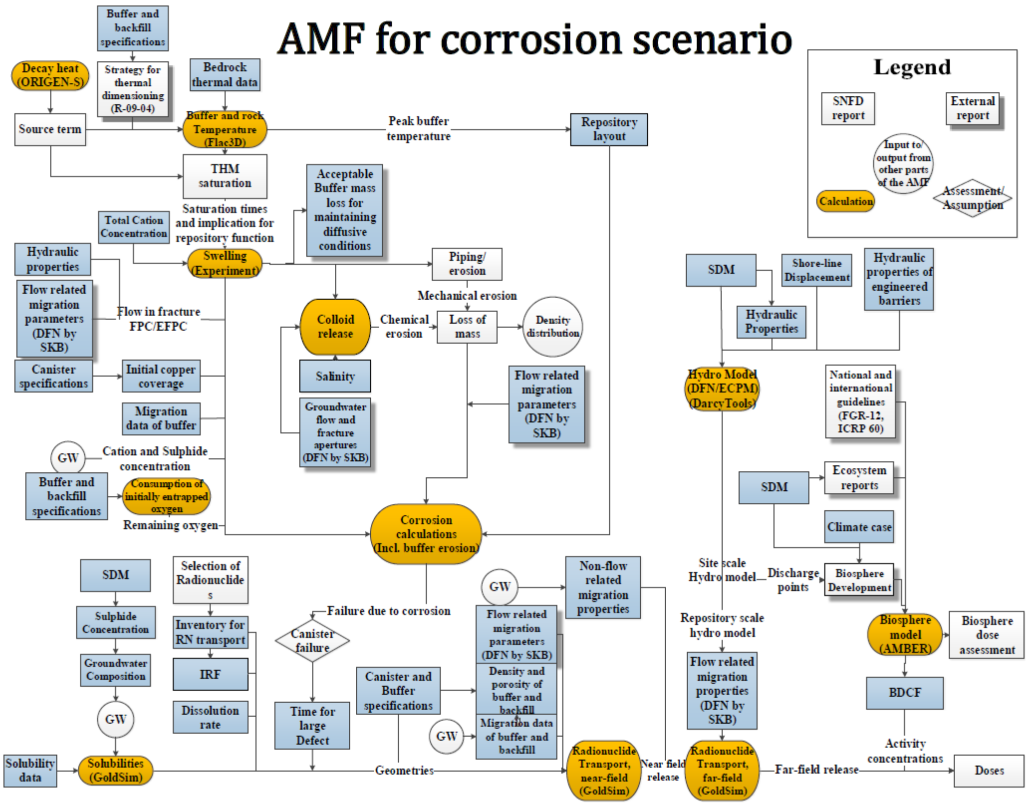
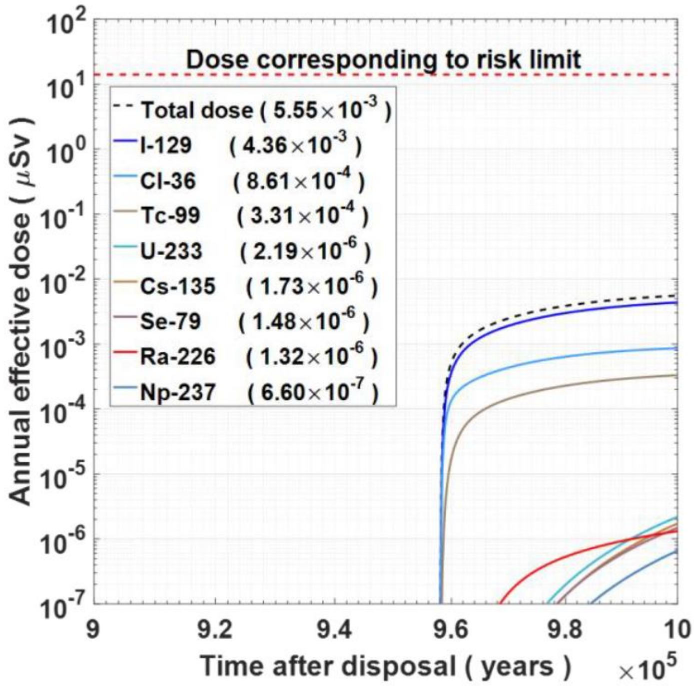


圖 20 ：SNFD2017 報告腐蝕情節安全評估模式鏈

(A)



(B)

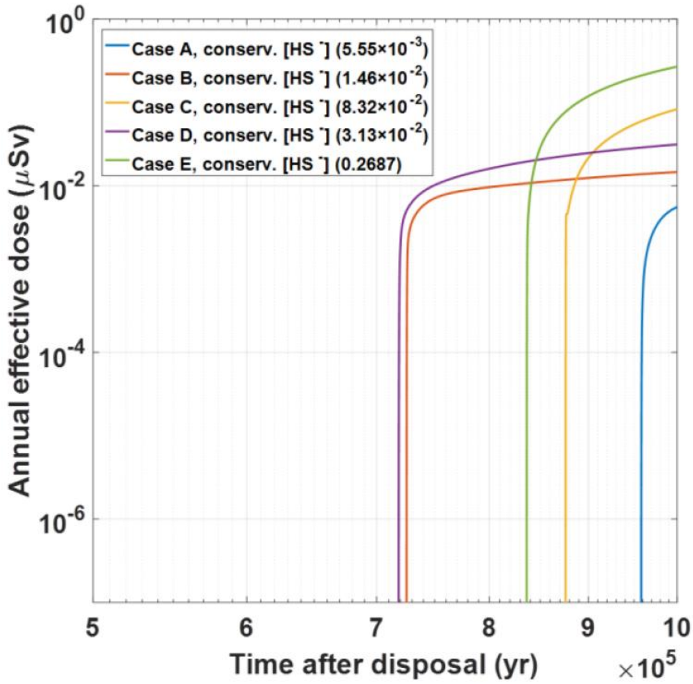


圖 21 ：SNFD2017 報告腐蝕情節劑量分析

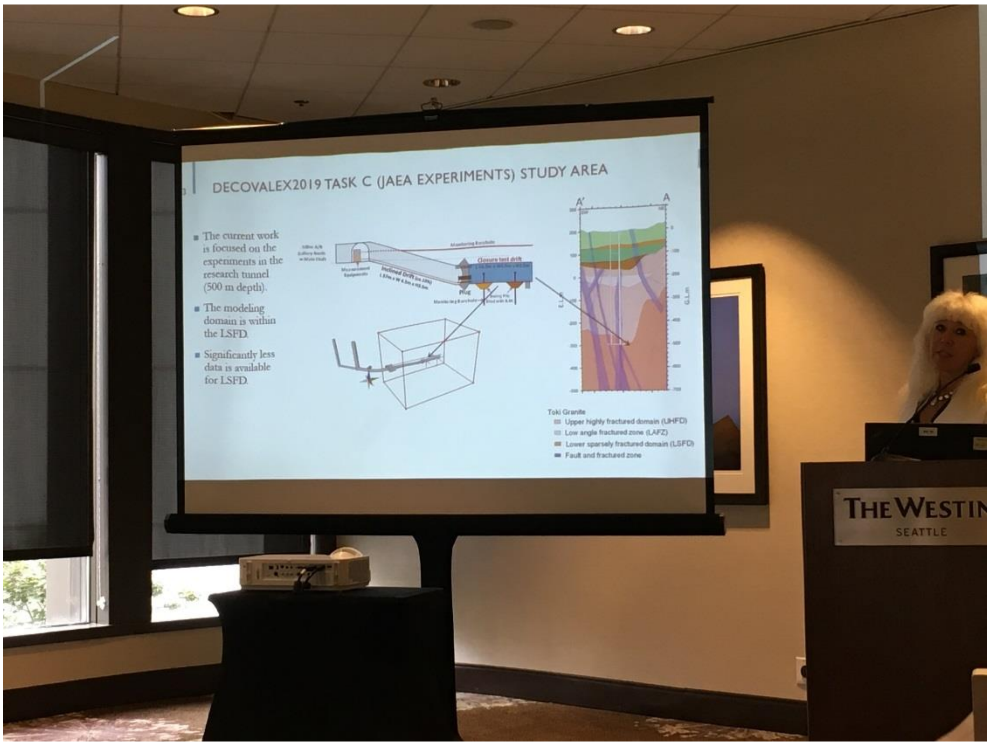


圖 22 ：以 MIU 為例建立 PFlotran 模擬驗證

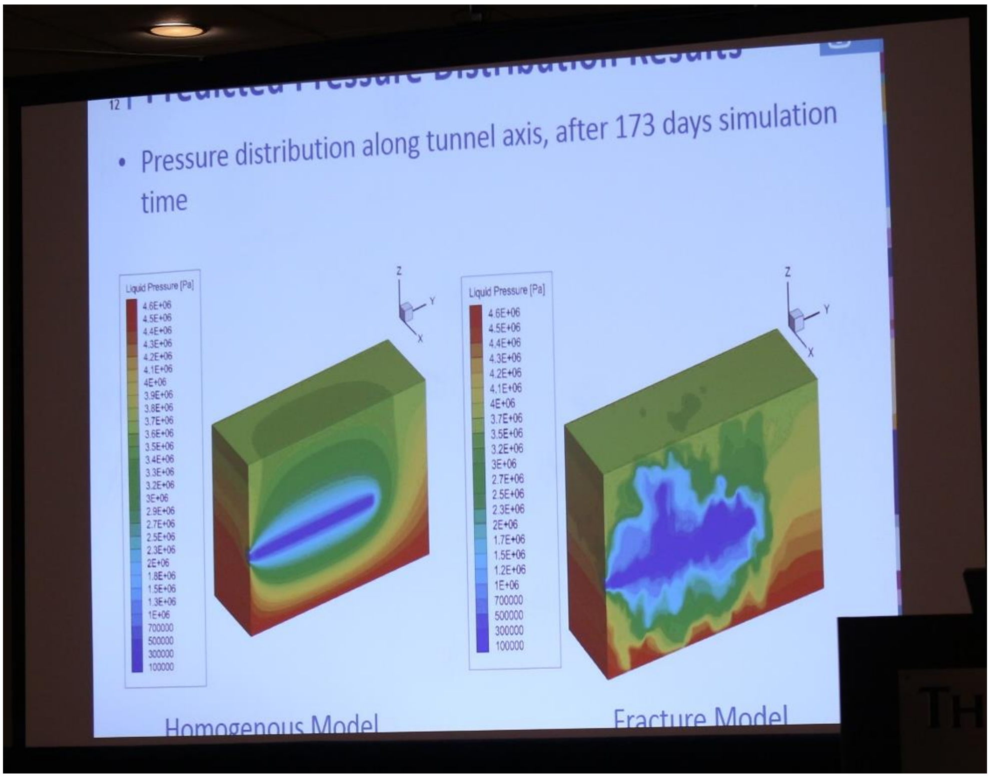


圖 23 ：以 PFlotran 分析 MIU 流場模擬結果

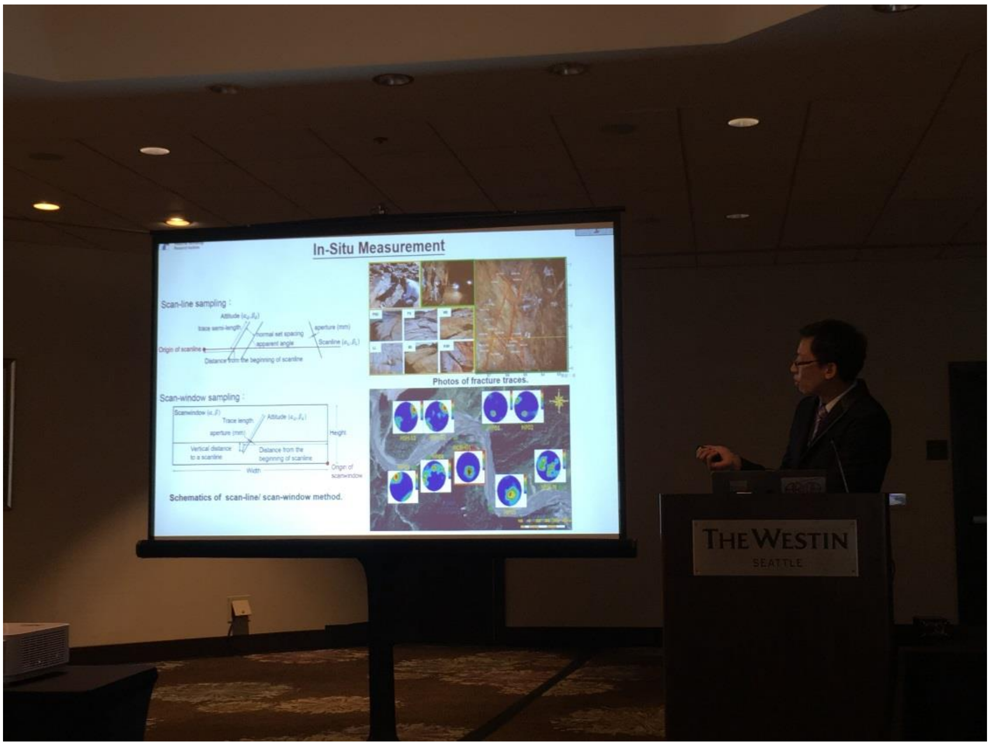


圖 24 ：現地裂隙調查與裂隙分布

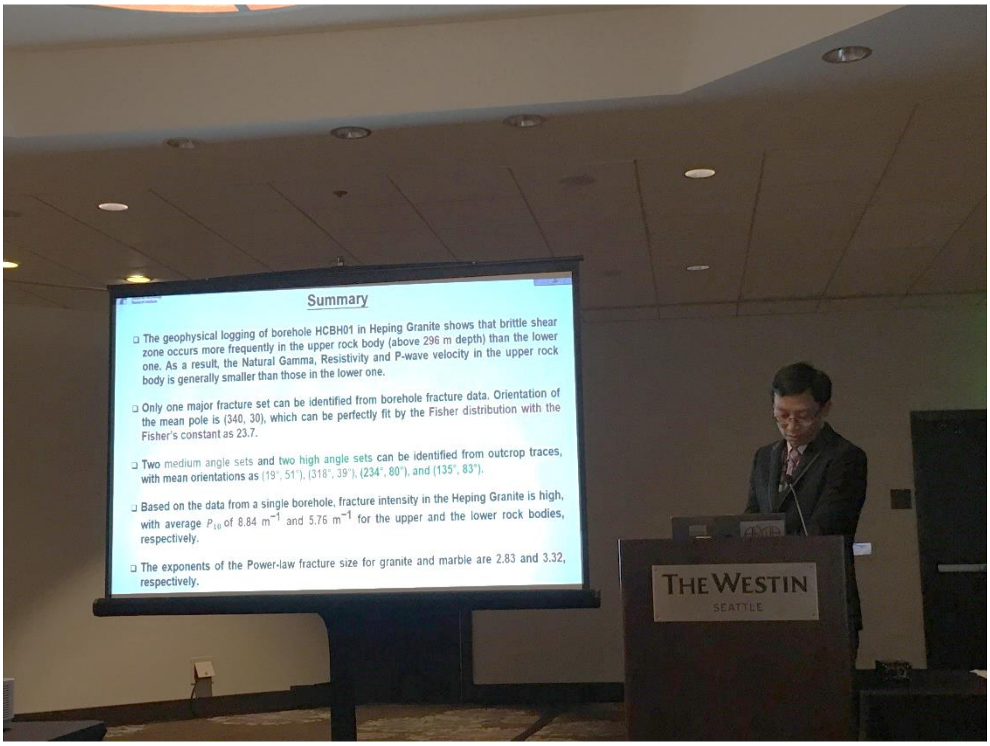


圖 25 ：現地調查與裂隙導水帶特性參數

圖 26 ：日本 NRA 內田雅大博士

圖 27 ：模式驗證流程圖

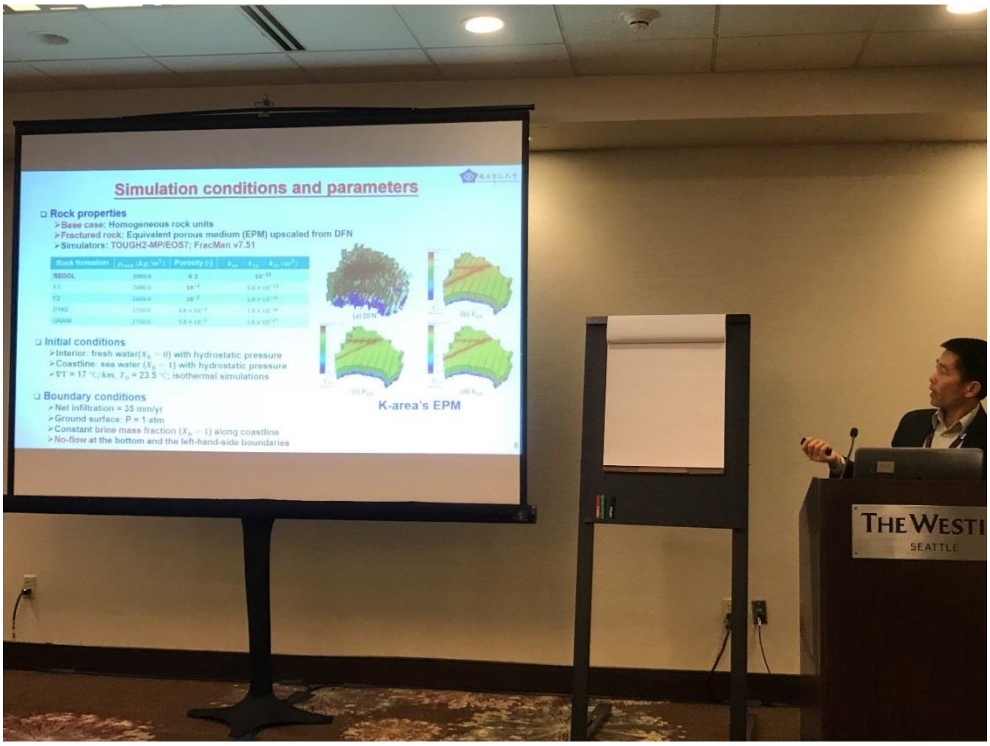


圖 28 ：SNFD2017 報告參考案例使用參數及模擬環境

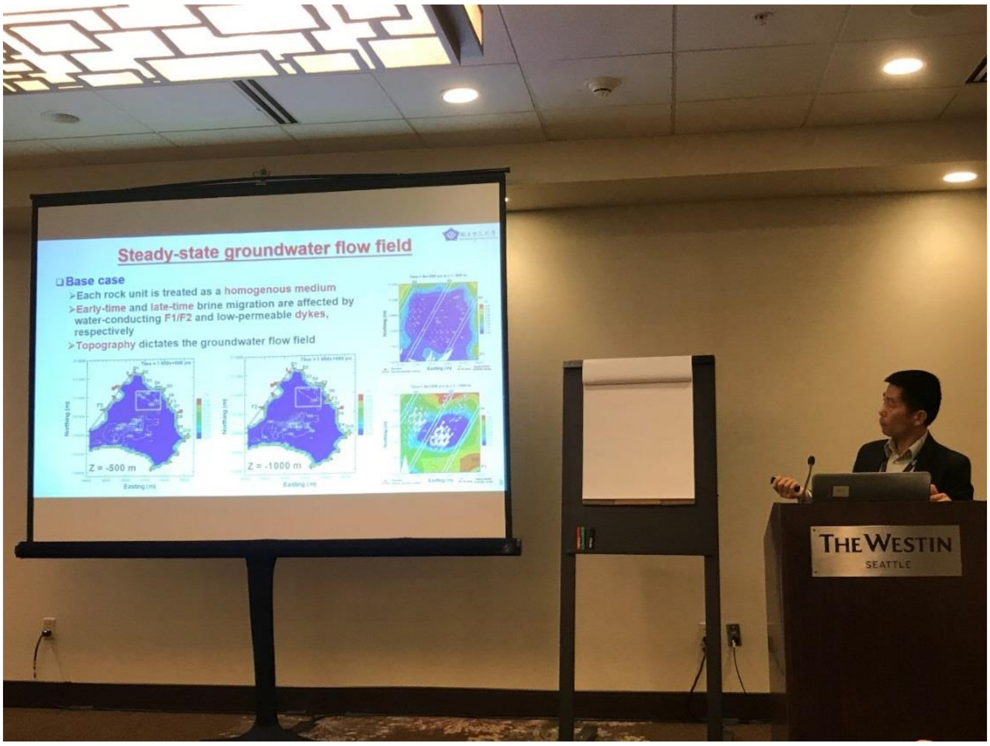


圖 29 ：穩定狀態下之流場分布

（三）專題論壇－裂隙尺寸論壇

本論壇於 DFNE 會議的第 3 天舉行，設定議題以輕鬆交流的方式，希望透過與會人員的共同討論，就目前 DFN 模式的理論及應用，激發出更多想法，論壇主題為離散網路模式中重要的參數「裂隙尺寸」，就其定義提出理論上及實務上的見解，會中不做結論，僅提供與會人員進一步思考參數及模式使用上可能需要注意的假設與前提。

論壇由 SKB 的 Raymond Munier 博士主持，Raymond 博士在 SKB 已服務將近 20 年，為構造地質方面的專家，會議首先由 Bill Dershowitz 博士說明，目前多數人採用冪函數分布作為裂隙尺寸分布(如圖 30)，但是冪函數分布的適用性與合理性，應有其假設前提，並於現場和與會人員交換意見，大多數人同意冪函數分布與裂隙之間並沒有特定的物理關係，但其統計分布特性較其他模式而言，較符合野外觀察到的裂隙尺寸分布特性，故現階段採用冪函數分布作為裂隙分布特性分析的假設前提尚屬合理，但在將裂隙統計資料應用至 DFN 模式前，應確認其適用性。

接下來由 Philippe Davy 博士說明由現地裂隙調查到 DFN 建模的過程與其理論假設(如圖 31)。現地調查可能採用地表裂隙測量、井孔攝影及坑道壁測量等，不同的方法所取得的裂隙資料有不同的代表性，在將這些不同現地調查資料特徵化時，應要注意不同取得方法可能潛藏的不確定性。在進行模式的選擇時，要考量特徵化後的裂隙特性、現地水力特性與大地應力的一致性，選用理想的模式與定義，以裂隙尺寸為例，要考量所選用的裂隙的尺寸，選擇使用機率分布(statistical distribution)、;常態分布(normal distribution)或是冪函數分布。在進行 DFN 的模式建立時，所使用的裂隙參數及數學模式，都會影響最後進行升尺度(upscaling)的結果，進而影響後續評估時的不確定性。

圖 30 ：裂隙分布的統計特性

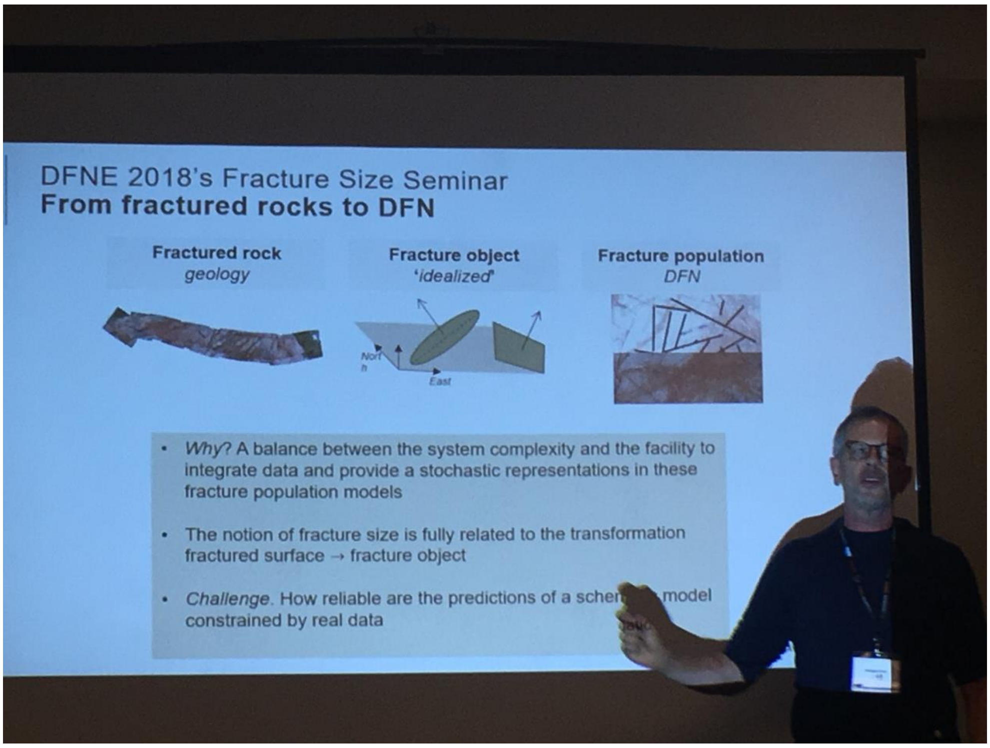


圖 31 ：DFN 建模與其理論假設

（四）海報發表

本次研討會台電公司大會主席邀請，希望能將我國在裂隙岩體的研究成果與國際社會分享，因此職李在平與邱琮翔專員分別投稿了 1 篇離散裂隙網路分析技術的應用論文，論文題目分別為：「Construction of DFN-based hydrogeological model using reference case data for SNF disposal in Taiwan.」及「The applications of discrete fracture network model for spent nuclear fuel final disposal program in Taiwan.」，論文內容詳如 附錄 III. 論文全文論文，發表海報詳如 附錄 IV. 發表海報。

上述論文係以用過核子燃料最終處置計畫第 1 階段成果 SNFD2017 報告為基礎，說明以一參考案例作為安全評估研究場址，進行 DFN 模式建立與地下水流場的初步測試之相關研究。本階段工作未涉及任何場址評選工作，僅就目前潛在處置母岩既有之現地調查資料，建立相關模式建立與評估技術。

海報展示期間，有多國放射性處置專責機構或研究機構專家，包括：加拿大 NWMO 專責機構；捷克 SÚRAO 專責機構；法國 CNRS 研究中心；日本原子力規制委員會；西班牙 AMPHOS21 顧問公司；美國 Sandia 國家實驗室、Lawrence Berkley 國家實驗室及 ITASCA 顧問公司及英國 RWM 專責機構等單位，對 SNFD2017 報告內容相當感興趣，多位專家於現場聆聽海報內容(圖 32)並詢問相關技術細節(圖 33)，專家對我國目前的技術發展成果表達肯定，並分享該國的技術發展經驗，以及建議未來可發展之方向。

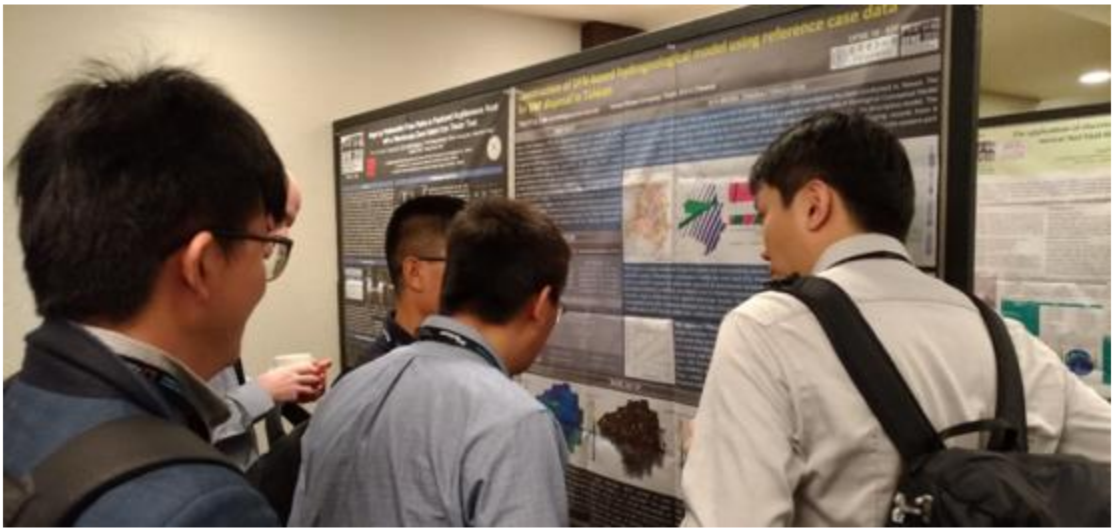


圖 32 ：國際專家聆聽 SNFD2017 報告研究成果

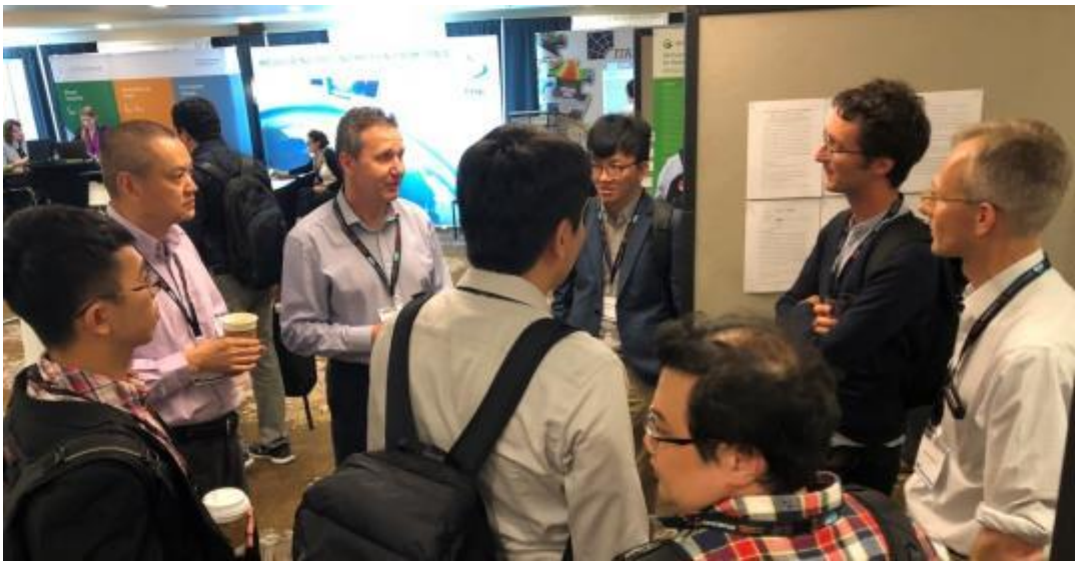


圖 33 ：與國際專家討論技術細節

三、拜訪 Golder Associates Inc.西雅圖分公司

1960 年 Golder 公司於加拿大多倫多成立，主要提供土壤力學及地表工程的專業諮詢服務，後續業務擴展至岩石力學、水文地質、水利工程、地下資源開發及地理資訊系統等領域。目前集團分為：工業製造、礦業、石油與天然氣、能源、運輸及城市發展與規劃等部門，主要提供的服務包括：自然資源規劃與評估、環境管理、工程設計與施工、水資源規劃與處理及大型計畫規劃、諮詢與管理等，分公司遍其全球。就 DFN 技術發展方面，Golder 公司開發的 FracMan 軟體為全球第一個 DFN 商用軟體，其開發目的原為協助進行石油及天然氣資源的評估與開採，目前相關功能已擴充至採礦、核能及土木工程領域。

目前台電公司亦採用 FracMan 軟體進行「用過核子燃料最終處置計畫」技術開發，並將其應用於水文地質模型、地下水流場評估、地震影響評估及設施安全評估等方面，受該公司邀請並為增加參與本次研討會的效益，故於會後拜訪 Golder 西雅圖分公司，與目前 FracMan 項目負責人韓裔 Lim Doo-Hyun 博士就目前 SNFD2017 報告採用之模式設定與 FracMan 執行上的問題進行意見交流，主要討論議題如下：

1. 質點傳輸運算與網格設定

   目前 SNFD2017 報告所採用之分析模式，係以 K 區為參考案例，模型採用 K 區的地表地形及陸海交界做為邊界，其輪廓較為複雜，在進行網格設定時，會因地質構造上的差異造成網格分布不均，導致後續進行質點傳輸運算時，部分質點會因網格節點(Node)判定問題，而停留在錯誤的地方(Stuck)。該問題經現場測試及初步討論，Lim 博士建議可從以下幾個方向著手：

   (1) 簡化模型輪廓，因輪廓外型曲折，目前採用的輪廓約由 8X 個面所組成，建議可適度簡化模型輪廓，降低輪廓面的數量，以降低

因地質構造差異造成網格不均的問題(圖 34)。

(2) 提高模擬精度，降低網格尺寸大小或增加相同模擬體積內的網格數，以降低網格接點的判定錯誤問題(圖 35)。

(3) 移除不連通的裂隙，進行模擬運算之前，先移除此法可加速模式的收斂，有助於提升分析結果(圖 36)。

(4) 增加模擬質點數量，考量模擬所需的時間及代表性，可透過增加質點的數量,避免為了解決少數 Stuck(可能<10%)而大幅增加模擬時間(可能>10 倍時間)。

2. 濃度計算

現階段 FranMan 僅能計算質點傳輸路徑，經詢問 Lim 博士軟體是否可以進行濃度計算。Dr. Lim 表示目前的模式僅能計算質點的傳輸時間與路徑，在不同的時間段(time step)下的質點沒有濃度上的意義。若要計算濃度，可將單位時間內網格內的粒子總數給定一濃度，並除以單位網格之體積作估算，但要注意目前模式可運算的網格數目上限為 20 萬個，節點數 200 個，若超過可能無法收斂。

3. 地質力學模組的應用

力學模組是 Fracman 核能版新完成開放使用的功能，Lim 博士概要說明了力學分析的功能與參數需求，主要可應用於隧道壁楔行破壞的分析、水力耦合描述應力與裂隙開口寬的變化關係、預測剪力強度與變形行為的分析、力學參數升尺度、斷層位移與應變分布等。

會後於 Golder 公司合影留念(圖 37)，結束本次拜訪行程。

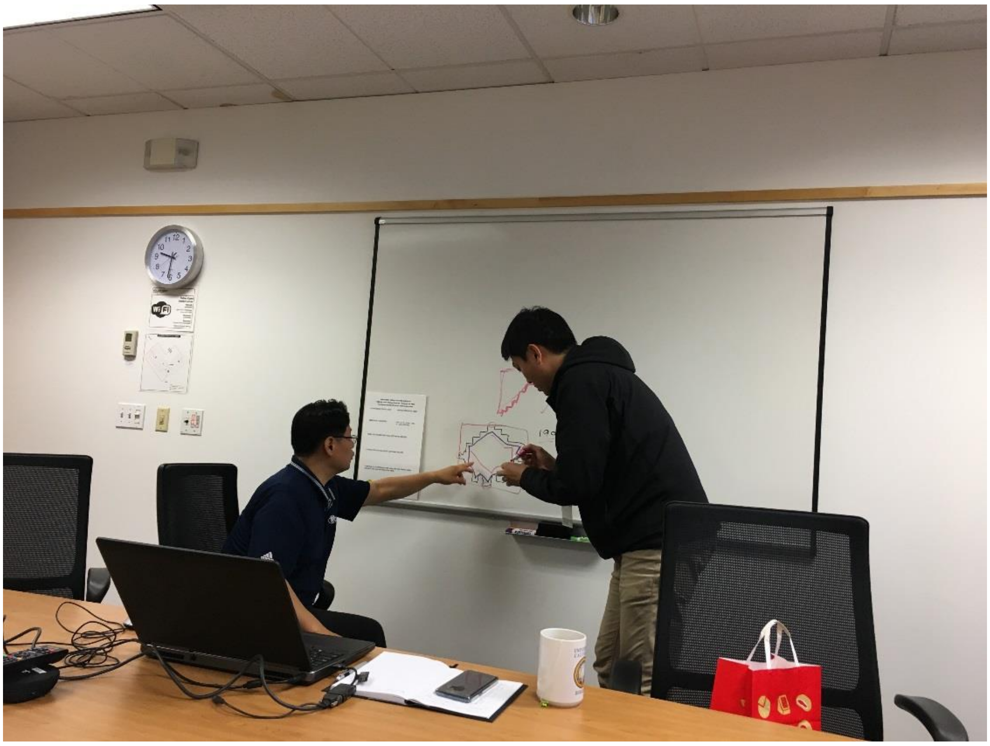


圖 34 ：透過簡化輪廓面的數量來提升模式運算

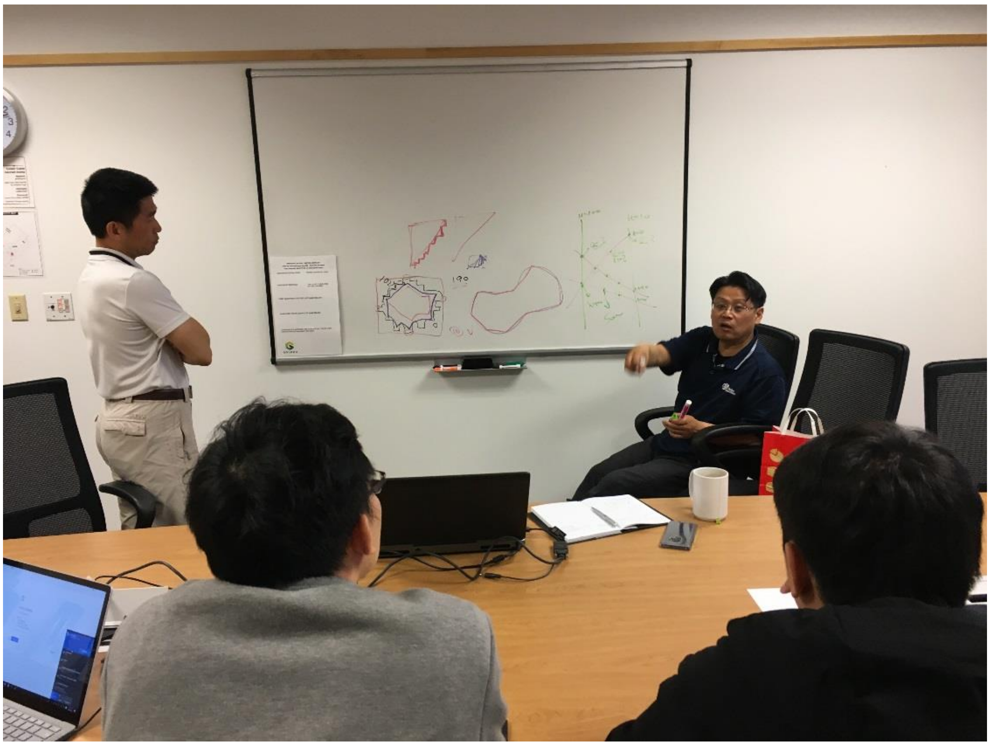


圖 35 ：改變網格尺寸以降低節點錯誤機率

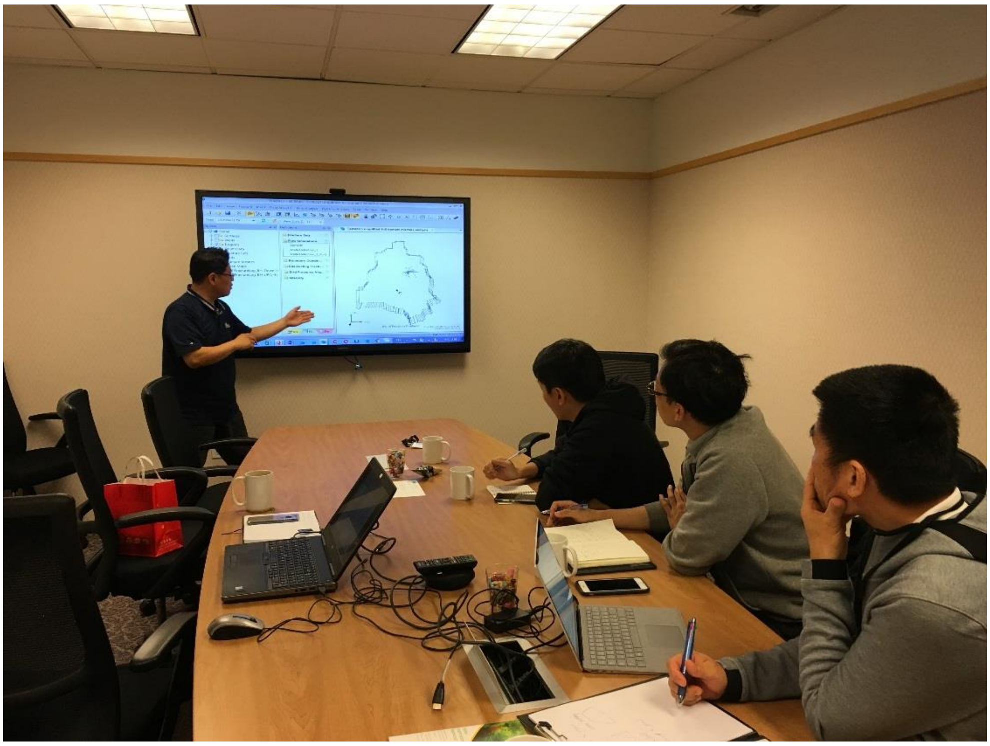


圖 36 ：於運算前先移除不連通的裂隙

圖 37 ：於 Golder 公司合影留念

肆、出國心得

本次赴西雅圖參加第 52 屆美國岩石力學年會及第 2 屆離散網路工程研討會，與各國專家就離散裂隙網路模擬技術與處置技術發展進行技術交流，除瞭解國際技術發展趨勢，亦讓國際專家瞭解我國處置技術之發展現況，著實獲益良多。

美國近年來受到地質鑽探與採礦工程技術的進步，以水力壓裂方法大量開採頁岩油及天然氣並產出許多的現地應力分析數據，進而吸引大量研究人員投入相關資源的評估與技術發展，從本次會議發表論文數量與即可發現。其中又以 DFN 模式評估結晶岩體或裂隙岩體內之流體行為主要發展項目之一，DFN 相關技術已大量運用於油氣開採、二氧化碳封存、地熱能評估及工程建設方面。此外，在放射性廢棄物的管理與處置方面，以結晶岩為處置母岩，基於深層地質處置及多重障壁概念所發展的的 KBS-3 處置概念亦被世界廣泛接受，並有多國以該概念為基礎發展其自有處置概念，相關評估亦以 DFN 模式為基礎。

目前 DFN 模式的建置流程大致為：

1. 進行現地調查作業並透過統計分析將調查結果化為合適的地質參數；
2. 選用適當數學模式，結合現地調查地質參數，建立 DFN 模式；
3. 應用模式分析，建立適合的地質模型，並將結果與現地資料驗證確認；
4. 修正模型並逐步精進

依地質環境本身即具有相當多的不確定性，從現地調查數據建立 DFN 模式的過程中，應就其數據來源、適用條件及判斷標準進行審慎的評估，以減少其不確定性；在模式選用方面，應瞭解其理論基礎、適用條件及地質參數特性等進行評估，以確保模式的合適性。

從芬蘭的經驗可以得知，惟有持續的技術精進與演練，將既有的地質調查資料進行定量化的分析與評估，以及各項模式的驗證、校準與現地資料的確認，提高模型的準確性，方可逐步提升對安全評估的信心，並可順利推展其相關規劃工作。

伍、建議

本次赴美國西雅圖參加 52nd RM/GS 2018 及 DFNE 2018 研討會，就與會經驗，相關建議如下：

一、 本次參加會議受惠於國際專家之經驗分享與指教，了解處置相關技術發展日新月異，惟有透過不斷精進方可持續與國際接軌，故應持續參加相關技術會議，透過與國際專家實際交流，持續與國際接軌，相關經驗與技術有助於處置技術之規劃，對推動處置計畫有相當助益。

二、 經聽取現場專家報告內容及經驗交換，目前就 SNFD2017 報告所採用之 DFN 模式，其資料取得方式與模式建立方法均與國際作法相近，惟因目前國內現地調查作業不易，在確認候選場址及取得現場調查作業之法律授權前，應持續進行實驗室研究以取得相關數據，以持續精進相關技術。

三、 目前 SNFD2017 報告採用之流場模擬與相關評估分析，經彙整與國際專家交流後的意見，未來應持續精進並強化模式的複雜性，提升預測模型之精準度，並透過驗證與確認，逐步提升信心指標。

四、 台電公司目前採用商用軟體 FracMan 進行 DFN 模式的建立與分析，與國際多個研究機構作法相近，考量未來若要納入地質應力模式，現階段應加強岩石力學參數相關試驗，以取得評估所需之相關參數(如楊氏係數、柏松比、節理面粗糙度及節理面抗壓強度等參數)。

五、 處置計畫執行期程長達 50 年，且涵蓋多項專業領域技術，包括：地質、地球物理、水文地質、核子工程、輻射防護、土木工程、機械材料、氣候變遷等，應持續培養相關人才庫，以確保相關智識及經驗得順利傳承。

六、附錄

附錄 I. 52nd RM/GS 2018 大會議程

RM/GS 2018 技術參訪與報到開幕

Friday, 15 June 2018	
07:00－18:00	**Technical Tour 1** **Snoqualmie Powerhouse and I-90 Rock Slope Stability**
Saturday, 16 June 2018	
08:00－18:00	**Technical Tour 1** **Whidbey Island Landslides, Lahars, Tsunamis, and Earthquakes**
14:00－16:00	**ARMA Committee on Strategic Planning**
Sunday, 17 June 2018	
07:30－09:00	**Registration and Speakers Ready Room** **Delegate Bags Sponsored by Itasca Consulting Group, Inc.**
08:30－16:45	**Workshop** **Workshop on Characterizing induced Seismogenic Potential** **Fifth Avenue Room**
08:30－16:30	**Short Course 1** **Microstructural Modeling of Rock Fracture: Bonded-Particle Modeling with PFC and Bonded-Block Modeling with 3DEC** **Whidbey Room**
08:30－16:30	**Short Course 2** **2D and 3D Modeling of Rock Fracturing Processes in Geomechanics** **Blakely Room**
09:30－15:30	**ARMA Board of Directors Meeting** **Orcas Room**
14:00－17:00	**Exhibit Set Up/Posters Mounted on Display Boards** **Grand Ballroom**
17:00－17:30	***Meeting of* Student *Assistants* Registration Desk**
18:00－18:15	***Opening* Session Grand Ballroom**

RM/GS 2018 研討會第 1 日

Monday, 18 June 2018				
07:00—18:45	**Registration and Speakers Ready Room**			
07:00—07:50	**Author's Breakfast**			
08:00—09:30	**Track A** **Fifth Avenue Room**	**Track B** **Cascade Ballroom I**	**Track C** **Cascade Ballroom II**	**Track D** **Elliot Bay**
	Technical Session 2	**Technical Session 6**	**Technical Session 10**	**Technical Session 14**
	Geomechanics of Unconventionals	***Geotechnical Laboratory and Field Testing***	***Experimental Studies***	***Geomechanics in Geothermal Processes***
08:30—16:30	**Exhibits Open**			
09:30—12:30	**Special Activity Seattle Sights Bus Tour**			
09:30—10:00	***Coffee Break, Exhibits***			
10:00—10:50	**Keynote Address** **Tony Dell, Engineering Specialist-Geotechnical, SNC Lavalin**			
11:00—12:30	**Track A** **Fifth Avenue Room**	**Track B** **Cascade Ballroom I**	**Track C** **Cascade Ballroom II**	**Track D** **Elliot Bay**
	Technical Session 2	**Technical Session 6**	**Technical Session 10**	**Technical Session 14**
	Hydraulic Fracturing Modeling	***General Geomechanics***	***Advances in the Simulation of Damage and Fracturing Processes in Rocks and Rock Masses I***	***Seismicity in Mining***
12:30—13:30	***Lunch(on Your Own)***			
12:30—13:30	**Lunch Meeting of the ARMA Publications Committee**			
12:30—13:30	**Lunch Meeting of the ARMA Technical Committee on Hydraulic Fracturing**			
12:30—13:30	**Meeting of the ASCE Rock Mechanics Committee**			
14:00—15:30	**Technical Session 3**	**Technical Session 7**	**Technical Session 11**	**Technical Session 15**
	Heavy Oil Geomechanics	***New Developments in Geomechanics***	***Advances in the Simulation of Damage and Fracturing Processes in Rocks and Rock Masses II***	***Ground Control in Coal Mining***
15:30—16:30	***Technical*** **Poster Session,** ***Exhibits, Coffee Break***			
16:30—18:00	**Track A** **Fifth Avenue Room**	**Track B** **Cascade Ballroom I**	**Track C** **Cascade Ballroom II**	**Track D** **Elliot Bay**
	Technical Session 4	**Technical Session 8**	**Technical Session 12**	**Technical Session 16**
	Sanding	***Reservoir Geomechanics***	***Developments in Backfilling Mining Stopes***	***Induced Seismicity and Microsesimic Monitoring***

RM/GS 2018 研討會第 2 日

Tuesday, 19 June 2018				
07:00—18:45	*Registration and Speakers Ready Room*			
07:00—07:50	*Author's Breakfast*			
08:00—9:30	Track A Fifth Avenue Room	Track B Cascade Ballroom I	Track C Cascade Ballroom II	Track D Elliot Bay
	Technical Session 17	Technical Session 21	Technical Session 25	Technical Session 29
	Casing/Cement/Formation Interations	*Hydraulic Fracturing Experimental*	*Slope Stability in Mines*	*Rock Physics and Geophysics for integrated Geomechanical Characterization*
08:30—16:30	*Exhibits* Open			
09:30—10:00	*Coffee Break, Exhibits*			
10:00—10:50	*2nd ARMA Distinguished Lecture* *Charles Fairhurst, Prof. Emeritus, University of Minnesota*			
10:30—13:30	*Special* Activity Guided Food and Historic *Walking* Tour of Pike Place Market			
11:00—12:30	Technical Session 18	Technical Session 22	Technical Session 26	Technical Session 30
	Salt and Injection Geomechanics	*Hydraulic Fracturing Geomechanics I*	*Slope Stability, Dams and Foundations*	*Imaging Technologies for Geomechanics*
12:30—13:30	*Lunch (on Your Own)*			
12:30—14:00	Lunch *Meeting* of the ARMA Future Leaders			
14:00—15:30	Track A Fifth Avenue Room	Track B Cascade Ballroom I	Track C Cascade Ballroom II	Track D Elliot Bay
	Technical Session 19	Technical Session 23	Technical Session 27	Technical Session 31
	Hydraulic Fracturing Geomechanics II	*Experimental Hydrothermal and Biological Rock Mechanics*	*Mining Case Histories*	*AE and NDE Techniques for Material and Microcrack Characterization*
15:30—16:30	*Technical Poster* Session, *Exhibits, Coffee Break*			
16:30—18:00	Track A Fifth Avenue Room	Track B Cascade Ballroom I	Track C Cascade Ballroom II	Track D Elliot Bay
	Technical Session 20	Technical Session 24	Technical Session 28	Technical Session 32
	Hydraulic Fracturing Special: Acid and Refrac	*Lab Studies: Unconventionals*	*Case Histories-Civil Engineering Projects*	*AE for Lab Scale Fracturing Monitoring and Microcrack Detection*

RM/GS 2018 研討會第 3 日

Wednesday, 20 June 2018				
07:00－14:00	**Registration and Speakers Ready Room**			
07:00－07:50	**Author's Breakfast**			
08:00－09:30	**Track A** **Fifth Avenue Room**	**Track B** **Cascade Ballroom I**	**Track C** **Cascade Ballroom II**	**Track D** **Elliot Bay**
	Technical Session 33	**Technical Session 37**	**Technical Session 41**	**Technical Session 45**
	Formation Laboratory Evaluations I	***Tunnels and Underground Structures***	***Wellbore Stability I***	***Coupled Processes, Fluid-driven Fracture, Caprock Integrity***
08:30－16:30	**Exhibits Open**			
09:30－10:00	***Coffee Break, Exhibits***			
10:00－10:50	**Keynote Address** **Andrew Bunger, Assistant Professor, University of Pittsburgh**			
11:00－12:30	**Technical Session 34**	**Technical Session 38**	**Technical Session 42**	**Technical Session 45**
	Formation Laboratory Evaluations II	***Numerical Modeling of Civil Engineering Projects***	***Wellbore Stability II***	***Pore-scale, Micro, and Nano Rock Mechanics***
12:30－13:30	***Lunch (on Your Own)***			
12:30－14:00	**Lunch Meeting of the Seattle and New York Organizing Committees**			
14:00－15:30	**Technical Session 35**	**Technical Session 39**	**Technical Session 43**	**Technical Session 47**
	Formation Stress Evaluations	***Numerical Modelling in Geomechanics I***	***Drilling General and Bit Geomechanics***	***CO_2 and CBM Geomechanics***
15:30－16:30	***Technical Poster Session*, Exhibits, *Coffee Break***			
16:30－18:00	**Technical Session 36**	**Technical Session 40**	**Technical Session 44**	**Technical Session 48**
	Hydraulic Fracturing Stress Evaluations	***Numerical Modelling in Geomechanics II***	***Ground Control in Hard Rock Mining***	***Injection Geomechanics***
18:00－18:15	**Closing Session**			

附錄 II. 2nd DFNE 大會議程

DFNE 研討會第 1 日

Wednesday, June 20			
08:30－09:30	**DFNE Opening Keynote Lecture - Pine** **Philippe Davy: DFN, why, how and what for, concepts, theories and issues**		
09:30－16:30	**ARMA Trade Show - Grand Ballroom III**		
09:30－10:00	**Refreshment Break - ARMA Trade Show**		
10:00－11:00	**ARMA Keynote Address - Grand Ballroom I/II** **Andrew Bunger: The Making of a Hydraulic Fracture Swarm**		
11:00－12:30	**Pine**	**Mercer/Denny**	**Elliott Bay**
	Solute Transport and Safety Assessment	***Surface and Underground Mine Stability***	***Constraining DFN Models from Data I***
12:30－14:00	***Lunch (on your own)***		
14:00－15:30	**Pine**	**Mercer/Denny**	**Elliott Bay**
	Geothermal and Hydrogeochemical Modeling	***DFN Approaches for Slopes and Tunnels***	***Constraining DFN Models from Data II***

DFNE 研討會第 2 日

<table>
<tr><th colspan="5">Thursday, June 21</th></tr>
<tr><td>09:00—10:00</td><td colspan="4">DFNE Thursday Keynote Lecture - Pine
Davide Elmo: DFN analysis and modelling as the key to a better understanding of rock mass behaviour</td></tr>
<tr><td>09:30—17:30</td><td colspan="4">DFNE Trade Show and Posters - Pike</td></tr>
<tr><td>10:00—10:30</td><td colspan="4">Refreshment Break - DFNE Trade Show</td></tr>
<tr><td rowspan="2">10:30—12:00</td><td>Pine</td><td>Mercer/Denny</td><td>Fifth Avenue</td><td>Grand Crescent</td></tr>
<tr><td>Advanced Hydraulic Fracturing Diagnostics</td><td>Rock Blocks and Comminution</td><td>DFN Flow Models</td><td>Groundwater Flow and Radionuclide Transport</td></tr>
<tr><td>12:00—13:30</td><td colspan="4">Lunch (on your own)</td></tr>
<tr><td>13:30—14:30</td><td colspan="4">DFNE Thursday Seminar – Pine
Approaches for Naturally Fractured and Stimulated Reservoirs</td></tr>
<tr><td>14:30—15:00</td><td colspan="4">Refreshment Break - DFNE Trade Show</td></tr>
<tr><td rowspan="2">15:00—16:30</td><td>Pine</td><td>Mercer/Denny</td><td colspan="2">Fifth Avenue</td></tr>
<tr><td>DFN Reservoir Case Studies</td><td>Wave Propagation in Fractured Media</td><td colspan="2">Dynamic Stress from Hydraulic Fracturing</td></tr>
<tr><td>16:30—17:30</td><td colspan="4">DFNE Poster Presentation Reception - Pike</td></tr>
</table>

DFNE 研討會第 3 日

Friday, June 22			
08:30—15:00	**DFNE Trade Show and Posters - Pike**		
09:00—10:00	**DFNE Friday Keynote Lecture - Pine Room** **Lee Hartley: DFN Modeling for Geological Repositories** **in Crystalline Rock in Sweden and Finland**		
10:00—10:30	**Refreshment Break - DFNE Trade Show**		
10:30—12:00	**Pine**	**Mercer/Denny**	**Fifth Avenue**
	Coupled Process DFN Modeling I	***Rock Mass Effective Properties***	***Site Characterization and Validation***
12:00—13:30	***Lunch (on your own)***		
13:30—14:30	**The First DFNE Fracture Size Seminar - Pine Room** **Your Chance to Advance DFN - An Interactive Approach to a Key DFN Conundrum**		
14:30—15:00	**Refreshment Break - DFNE Trade Show**		
15:00—16:30	**Pine**	**Mercer/Denny**	**Fifth Avenue**
	Coupled Process DFN Modeling II	***DFN Rock Mass Modeling***	***Computational Improvements to DFN Flow***

附錄 III. 論文全文

附錄 III-1 ：Construction of DFN-based hydrogeological model using reference case data for SNF disposal in Taiwan

DFNE 18–820

Construction of DFN-based hydrogeological model using reference case data for SNF disposal in Taiwan

Tsai-Ping, Lee
Taiwan Power Company, Taipei, R.O.C.(Taiwan)

ABSTRACT: Taiwan Power Company (TPC) has responsibility to well manage the spent nuclear fuel generated from three nuclear power plants in Taiwan and to plan domestic final disposal facilities according to the nuclear related Act in Taiwan. We adopted the KBS-3 disposal concept developed by Swedish SKB at present to develop our disposal technology capabilities. An offshore island mainly composed of crystalline rock was chosen for research and development purpose and regarded as a reference case in our Technical Feasibility Assessment Report on Spent Nuclear Fuel Final Disposal. A simplified conceptual geological model was established based on 6 boreholes (up to 500-meter depth) and surface survey. The fracture analyses and statistical DFN description were conducted based on the geophysical logging data and outcrop measurements to generate a DFN model. The equivalent continuous porous medium (ECPM) approach was then implemented to simulate regional groundwater flow. These results could provide the needed performance measures for the following radionuclide transport and safety assessment.

1. INTRODUCTION

According to the Taiwan's "Nuclear Materials and Radioactive Waste Management Act", the waste producer is responsible for the waste management, storage and final disposal. Therefore, Taiwan Power Company has submitted a Spent Nuclear Fuel Final Disposal (SNFD) Plan to regulatory authorities since 2004 and re-evaluated every 4 years. The updated version was modified in 2014, and then approved by Atomic Energy Council in 2015.

Because deep geological disposal remains the preferred option for waste management of spent nuclear fuel and high-level radioactive waste in most countries, we adopted the KBS-3 disposal concept developed by Swedish SKB at present to develop our disposal technology capabilities. Currently, we have made a lot of efforts to show we do have potential host rock in Taiwan and tried to characterize it. An offshore island mainly composed of crystalline rock was chosen for research and development purpose and regarded as a reference case in our Technical Feasibility Assessment Report on Spent Nuclear Fuel Final Disposal (abbreviated as the SNFD2017 report).

Following the arranged 5 stages in the SNFD Plan, we are ready to complete the first milestone of potential host rock characterization and then move to the next stage of candidate site selection. During the stage of candidate site selection, we will complete the survey of recommended area, establish our performance and safety assessment capabilities, and finally propose at least 2 priority sites for detailed investigation at the end of this stage.

In this study, the field data of the eastern reference island we called K area were summarized and reviewed. A DFN recipe established for this area is used to construct a simplified hydrogeological model by Fracman. The DFN related methods and analysis results were then applied in the SNFD2017 report.

2. DFN MODEL CHARACTERIZATION

At present, there is no candidate site has been proposed and no systematic detailed field investigation has been conducted in Taiwan. The reference case is just a hypothetical platform for technical development. There is a data list we called Table-II (Geological Conceptual Model and Characteristic Data) which is mainly collected form the K area and based on the data compiling structure of a site descriptive model. The needed parameters were illustrated by combining the limited fracture and surface lineament survey data, well logging records from 6 research boreholes, and proper assumptions which are refer to the SKB's SR-site report (SKB, 2011).

2.1. *Geological Setting*

The K area is referring to the eastern part of an offshore island located at western Taiwan strait. A preliminary geological conceptual model of K area has been developed and proposed in SNFD2017 report as Fig.1. The map also demonstrates the location of survey outcrops, investigation lines, and research boreholes.

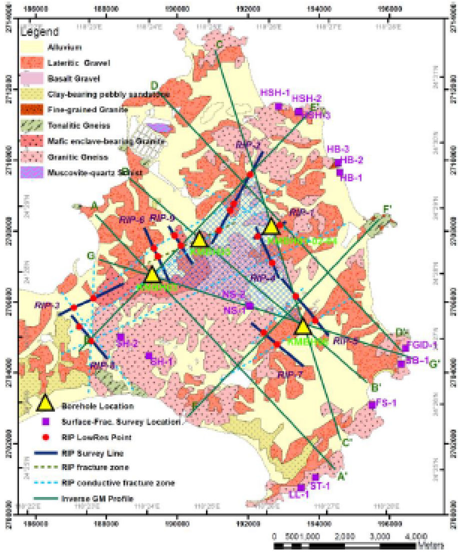


Fig. 1. Geological map of K area.

The K area is mainly composed of granitic gneiss and intersected by several dolerite dikes and fault zones. Following the conceptual model, the main fault (F1), Fracture zone (F2), and 10 explicitly represented dikes are regarded as deterministic structures in this study. The geometries of F1, F2, and the dolerite dikes are shown in Fig. 2.

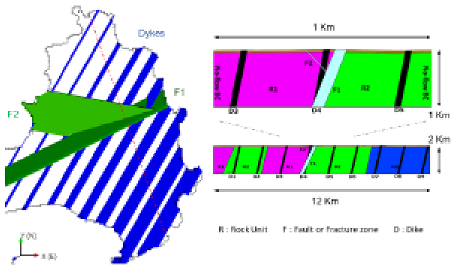


Fig. 2. Locations of fault zone, fracture zone, dike, and rock unit. The profile of red dash line is shown in right.

2.2. *Borehole Data*

Because the imaginary facilities are located in the northeast of K area and within the range of R1 rock unit, boreholes KMBH01 to KMBH05 are mainly used for fracture characterization (Lin et al., 2003, Chang et al., 2003, Guo et al., 2003). The fracture intensity data is referring to the optical televiewer records for Table-II, we also conducted an alternative analysis using acoustic televiewer records for comparison as uncertainty research in the future. The fracture intensities are represented using the cumulative fracture intensity (CFI) graphs with depth as Fig. 3.

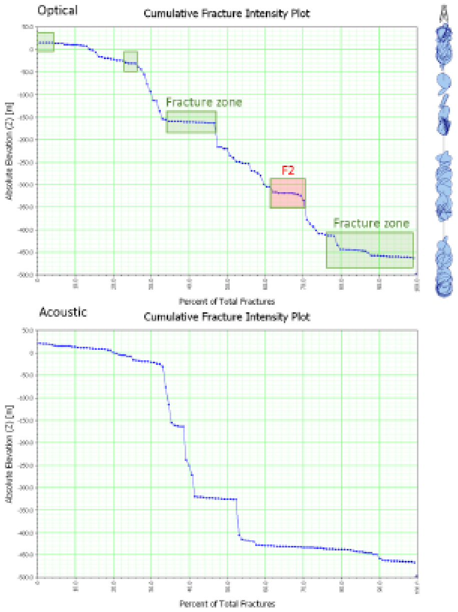


Fig. 3. Plot of cumulative fracture intensity with depth at KMBH01.

The colored area in Fig. 3 represents the known fault zone and fractured zone confirmed by core logging. A maximum Terzaghi weight of 7 (Terzaghi 1965) was then used to correct the linear fracture intensity (P_{10}). The corrected P_{10} values are similar at nearby boreholes (KMBH01, 02, 04) and KMBH03, but higher at KMBH05. The apparent difference of fracture intensity (P_{10}) with depth illustrates that there is a boundary between regolith and lower less weathered granitic rock. The thickness of 70 m to this boundary is estimated. According to the Table-II, the averaged P_{10} value of lower fracture domain is about 0.3 m^{-1}, the P_{10} value is much higher to 2.4 m^{-1} for the upper fracture domain.

Fig. 4 illustrates the equal-area and lower-hemisphere stereonets for fracture pores, the fracture orientation analysis is calculated only from KMBH01 to KMBH04 in accordance with the Table-II. According to the Fisher distribution, there are four main fracture clusters identified in the upper fracture domain. A main proportion of sub-horizontal fractures with a fracture dip close to about 10 degrees is observed. However, another steep fracture cluster could dominate the preferential flow path. Regarding the lower fracture domain, the orientation and proportion of fracture are divided into five main clusters. These results reanalyzed from borehole raw data are consistent with the Table-II.

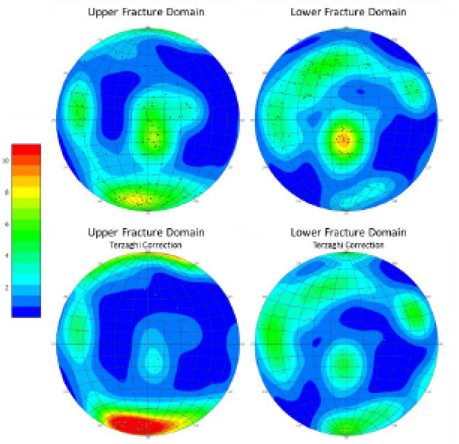


Fig. 4. Borehole fracture orientations for upper fracture domain and lower fracture domain. Top represents no correction; bottom is corrected by Terzaghi method.

2.3. *DFN Parameters*

The fractures related parameters used for constructing DNN-based hydrogeological model are shown in the section07 of the Table-II. The fractures are generated according to the Univariate Fisher orientation distribution as Fig .4. Each fracture cluster is defined using trend, plunge, and concentration (κ). The spatial arrangement of fracture centers is assumed by stationary random (Poisson) process. About the fracture size distribution (k_r), a power law shape factor of 2.6 is suggested. The minimum radius value is set by 0.1 m for the location parameter (r_0). We also applied a truncated fracture size distribution with a minimum fracture radius of 4.5 m, and the maximum fracture size is limited by 564 m. The range is determined through the relation

$$P_{32}(r_{\min}, r_{\max}) = \frac{\left[r_{\min}^{2-k_r} - r_{\max}^{2-k_r}\right]}{r_0^{2-k_r}} \cdot P_{32}(r_0, \infty) \qquad (1)$$

where $P_{32}(r_{min}, r_{max})$ is the spatial fracture intensity corrected with determined fracture radius between the minimum and maximum fracture size (La Pointe et al., 2008, Follin et al., 2006). It is noticed that the minimum fracture size of 4.5 m is recommended instead of 5.64 m in order to enhance the connectivity. The relative fracture intensity for each fracture clusters is evaluated. The spatial fracture intensity P_{32} is assumed to be congruent with the corrected linear fracture intensity P_{10} (Table 1).

Table 1. DFN Recipe for K area (Modified from TPC, 2017)

Fracture property	Upper fracture domain (< 70 m)	Lower fracture domain (> 70 m)
Fracture Clusters (Univariate Fisher)	Trend / Plunge / κ / P Cluster 1: 198˚/ 18˚/ 18/ 26% Cluster 2: 155˚/ 4˚/ 15/ 24% Cluster 3: 264˚/ 23˚/ 16/ 18% Cluster 4: 98˚/ 81˚/ 11/ 32%	Trend / Plunge / κ / P Cluster 1: 65˚/ 17˚/ 20/ 15% Cluster 2: 344˚/ 38˚/ 18/ 24% Cluster 3: 281˚/ 29˚/ 16/ 30% Cluster 4: 174˚/ 22˚/ 17/ 10% Cluster 5: 175˚/ 75˚/ 19/ 21%
Fracture Location	Stationary random (Poisson) process	
Fracture intensity	P_{32} = 2.4	P_{10} = 0.3
Fracture size (Power law)	k_r = 2.6 k_r: exponent of fractal dimension r_0 = 0.1 m r_0 : minimum radius value r_{min} = 4.5 m r_{max} = 564 m	
Fracture Transmissivity (m^2/s)	$T = 9.0 \times 10^{-9} \times (r)^{0.7}$ r: radius (m) of a disk fracture	$T = 5.3 \times 10^{-11} \times (r)^{0.5}$ r: radius (m) of a disk fracture

Due to the lack of detailed hydraulic test for K area at present, there are no sufficient data and suitable relation developed between fracture parameters and fracture transmissivity. Refer to the Swedish Forsmark site, the following empirical equations are recommended in Table-II for the Fracman MAFIC

$$T_{Upper\ domain} = 9.0 \times 10^{-9} \times (r)^{0.7} \qquad (2)$$

$$T_{Lower\ domain} = 5.3 \times 10^{-11} \times (r)^{0.5} \qquad (3)$$

where r is the radius (m) of a disk fracture (Vidstrand et al., 2010). A power law relationship between fracture transmissivity and fracture radius is shown in Fig. 5.

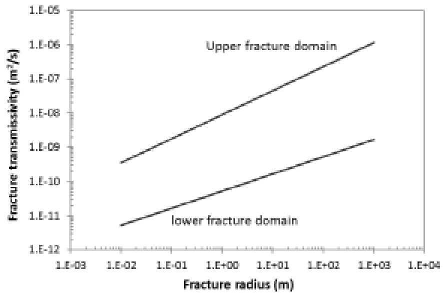


Fig. 5. Relationships between fracture transmissivity and fracture radius.

The transport aperture of fractures is defined as

$$e = 0.5\sqrt{T} \qquad (4)$$

where e is the transport aperture (m) of a fracture, T is the transmissivity (m^2/s) of a fracture. (Follin et al, 2005).

3. MODEL SET-UP

3.1. Model Domain

The model domain covers all the terrestrial part of K area. The grid was generated from a decimated topography surface of a 100 m scale triangular surface to the depth of -2,000 m (Fig. 6). There is total amount of 590,400 cells at a grid discretization of 120 × 120 × 41. The refinement was hierarchically applied from surface to the depth of -500 m where is the location of imaginary repository.

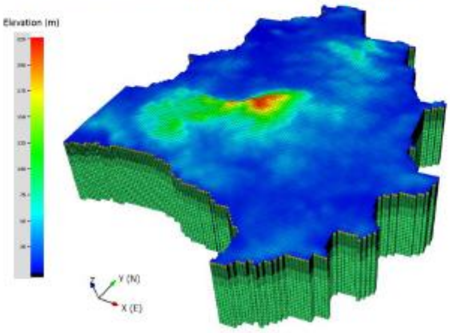


Fig. 6. Model domain with surface topography and grid. The upper domain is colored in yellow. The lower domain is colored in green.

The upper domain (above 70 m depth) and lower domain (below 70 m) were mainly modelled by equivalent continuous porous medium (ECPM) after fracture generation and upscaling. A small specific DFN domain (1,400 m × 1,400 m × 400 m) was placed around the repository (Fig. 7 and Fig. 8) inside the lower domain to implement hybrid DFN approach using Fracman.

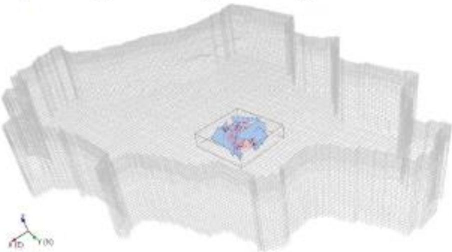


Fig. 7. Hybrid DFN model domain and repository location.

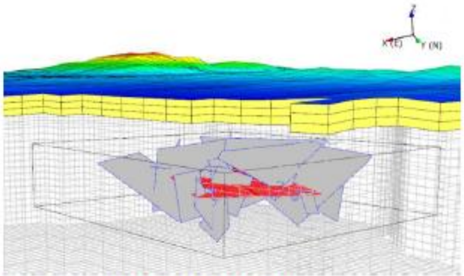


Fig. 8. Zoom of the hybrid DFN model domain.

3.2. Fracture Generation

Fig. 9 represents a single realization of fracture generation which consists of total 21,017,366 fractures based on the parameters listed in Table 1. The upper domain reveals higher fracture transmissivity of about 10^{-7} to 10^{-5} m^2/s. The fracture transmissivity of lower domain ranges from 10^{-9} to 10^{-8} m^2/s. These fractures were used to provide the up-scaled properties for the ECPM regional scale model. After clipping fractures out of the specific DFN domain, there are still 94,877 fractures remained for the hybrid analysis, and 10,122 of the generated DFN fractures are connected to the specific domain boundary.

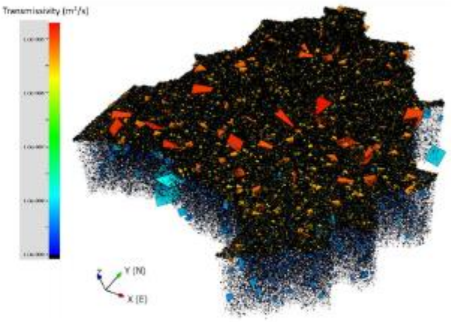


Fig. 9. The sample of one DFN realization, where each fracture is shown by its color with transmissivity.

3.3. Deterministic Structures

The fault (F1) and fracture zone (F2) illustrated in Fig. 2 are regarded as main permeable conduits with assigned hydraulic conductivity of 5×10^{-6} m/s. The F1 is a NE-trending normal fault with orientation of N64°E strike and 70°N dip. The width is set to 200 m. The strike and dip of F2 is N80°W and 80°N respectively. The width is set to 20 m. The 10 dikes of 100 m wide are believed to have lower hydraulic conductivity of 1×10^{-11} m/s than the surrounding rock mass of 1×10^{-10} m/s (Fig. 10).

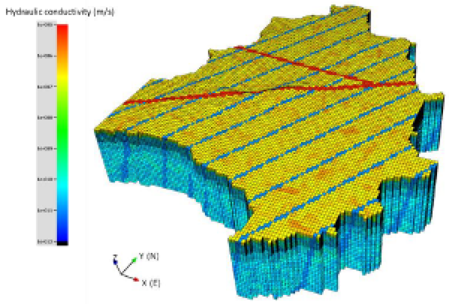


Fig. 10. Up-scaled hydraulic conductivity values (k_{xx}) in the x direction.

3.4. *Upscaling*

Appropriate setting for the characterization of fracture permeability was described in section 2.3 and 3.2, the Oda analysis (Oda, 1985) was then performed using Fracman upscaling code (Dershowitz et al., 1998) to calculate the hydraulic conductivity tensor components of each direction. Therefore, the fracture size and connectivity were not considered due to the limitation of upscaling method. The resulting up-scaled hydraulic conductivity in both x direction (k_{xx}) and y direction (k_{yy}) all mainly ranged from 10^{-11} to 10^{-6} m^2/s. The minimum hydraulic conductivity in z direction (k_{zz}) is lower to about 10^{-12} m^2/s (Fig. 10).

3.5. *Repository*

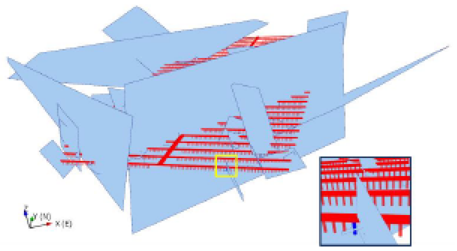


Fig. 11. Example realization. Upper part shows the intersected fractures to the deposition holes. Lower part is a close-up view of the yellow square.

According to the SNFD2017 report, a conceptual underground facility with reference layout composed of a 1,200 m long main tunnel and 62 deposition tunnels is proposed. The disposal tunnels are designed to be 300 m in length, 4.8 m in height, 4.2 m in width, and 40 m apart. The deposition holes are 7.8 m in height, 1.75 m in diameter, and 6 m apart. The imaginary repository is positioned on the north-east part of the K area. The analysis of fracture intersection and fractures connection around repository are conducted to provide an imaginary release point due to the failure of deposition hole. There are total 88 fractures intersecting the deposition holes in one single realization. One of the intersected deposition hole shown in Fig. 11 with blue color was used to analyze the release path.

3.6. *Boundary Condition*

According to the reference case, the hydraulic head was assumed to be equal to the elevation. Several different combinations of lateral and bottom boundaries were conducted for the SNFD2017 report. A simplified assumption with no-flow boundaries was then assigned for safety assessment like this study. The constant head can be described as a coefficient to X, Y, and Z dimensions, so the initial head was given by

$$H(x,y,z) = H_x x + H_y y + H_z z + H_0 \quad (5)$$

Where H_z is assigned to be 1 and others are zero for the consistency of assumption.

4. RESULTS

The resulting head distribution of regional ECPM model is illustrated in Fig. 12. It is clearly seen how the head distribution affected by the topography. Comparing the results to the SNFD2017 report, some slight difference may come from the different lateral boundary geometry and less cells in this study. To analyze the flow path especially in DFN model, reducing the cells in the hybrid model is necessary due to the limitation of program. Groundwater flow analysis for this simplified hybrid DFN model is then performed using the same condition as shown in Fig. 12.

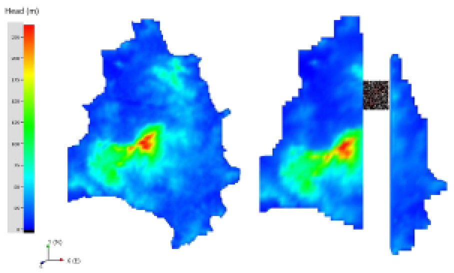


Fig. 12. Hydraulic head distribution of regional ECPM model (left) and simplified hybrid DFN model (right).

Based on this simplified model, preliminary particle tracking analysis was tested originating from the supposed failure canister in the deposition hole shown in Fig. 11. The results are shown as Fig. 13. The upward traveling particles may be influenced by the resultant local gradient from the hill around.

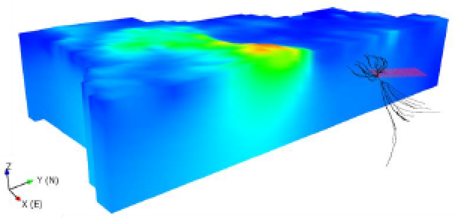


Fig. 13. Example of particle tracking on a vertical slice in the YZ plane of simplified hybrid DFN model.

5. CONCLUSION

The DFN related parameters for Taiwan's reference case were reviewed and reanalyzed. A DFN-based hydrogeological model was constructed using Fracman by considering both deterministic structures and stochastic fractures. Because it is not feasible to conduct groundwater flow analysis using all generated fractures, the ECPM approach was applied and a DFN model remained around repository was combined as a hybrid model. A preliminary analysis for steady state groundwater flow was performed consistent with the SNFD2017 report. Particle tracking calculations were tested using the simplified model. Such a process for DFN model construction will keep developing to provide necessary performance measures for the following radionuclide transport and safety assessment.

ACKNOWLEDGEMENTS

The author would like to acknowledge the experts from ITRI, INER, Sinotech Engineering Consultants, Inc. for the assistance of data integration and model construction. I am also thankful for the knowledge sharing and helpful suggestion by Sven Follin, Jan-Olof Selroos, and Patrik Vidstrand.

REFERENCES

1. Chang C.S., Lin W., and Chien J.M. 2003. Surface Fracture Measurement and Statistic Analysis of K- area. SNFD-ERL-90-192. (in Chinese)
2. Dershowitz, W., La Pointe, P., Eiben, T. and Wei, L. 1998. Integration of discrete feature network methods with conventional simulator approaches.
3. Follin S, Stigsson M, Svensson U, 2005. Regional hydrogeological simulations for Forsmark –numerical modelling using DarcyTools. Preliminary site description Forsmark area – version 1.2. SKB R-05-60, Svensk Kärnbränslehantering AB.
4. Follin S, 2008. Bedrock hydrogeology Forsmark. Site descriptive modelling. SDM-Site Forsmark. SKB R-08-95, Svensk Kärnbränslehantering AB.
5. Guo, T.R., Chang, C.S., Tong, L.T., Li, Y.H., Chen, W.S., Huang, and Y.T. 2003. BH1 and BH2 Geophysical Well Logging Report on K area. SNFD-ERL-90-195. (in Chinese)
6. La Pointe P., Fox A., Hermanson J., Öhman J. 2008. Geological discrete fracture network model for the Laxemar site. Site descriptive modelling, SDM-Site Laxemar. SKB R-08-55, Svensk Kärnbränslehantering AB.
7. Lin W., Chang C.S., and Hsu, C. 2003. KMBH02 and KMBH03 Drill-hole Report. SNFD-ERL-90-191. (in Chinese)
8. Oda, M.1985. Permeability tensor for discontinuous rock masses: Geotechnique, v. 35, no. 4, p. 483.
9. SKB. 2011. Long-term safety for the final repository for spent nuclear fuel at Forsmark. Main report of the SR-Site project. Svensk Kärnbränslehantering AB, SKB TR-11-01, Stockholm, Sweden, Report, 893 pp.
10. Terzaghi R D. 1965. Sources of error in joint surveys. Geotechnique 15, 287–304.

附錄 III-2 ：The applications of discrete fracture network model for spent nuclear fuel final disposal program in Taiwan

DFNE 18–919

The applications of discrete fracture network model for spent nuclear fuel final disposal program in Taiwan

Tsung-Hsiang Chiu
Taiwan Power Company, Taipei, Taiwan, R.O.C.

ABSTRACT: As the owner and operator of all NPPs in Taiwan, Taiwan Power Company (TPC) is responsible for the management of high level radioactive waste. According to the R&D results of TPC, TPC has accomplished "The Technical Feasibility Assessment Report on Spent Nuclear Fuel Final Disposal (SNFD2017 Report)" to make sure that the geological condition of Taiwan is suitable for geological disposal. The geological conceptual model developed in SNFD2017 Report is based on the geological, geophysical and geochemical surveys conducted on K area, which is a granitic offshore island. A hydrogeological conceptual model is constructed according to 6 boreholes logging data. Furthermore, all information derived from field data and in-situ hydraulic tests are reorganized as needed by DFN recipes. In the preliminary stage, TPC has been required to develop various underground assessment techniques which will be used under fractured crystalline rock environment. Basing on this SDM, a preliminary safety assessment and safety case have been accomplished. All the results have been integrated to "Taiwan case" in SNFD2017 Report.

1. INTRODUCTION

In 1979, the first nuclear power plant (NPP) was launched in Taiwan. In 2017, 6 reactors are still in service in 3 NPPs. Being the owner and operator of all NPPs in Taiwan, Taiwan Power Company (TPC) has been requested by the government to be responsible for both the management and disposal of radioactive waste. The R&D programs (Research and Develop programs) for the spent nuclear fuel disposal were executed in 1986, and the "Spent Nuclear Fuel Final Disposal (SNFD) Plan was submitted in 2004. The schedule of the SNFD can be divided into five stages as following:

(i) Investigation and Evaluation of the Potential Host Rock (2005 to 2017)
(ii) Selection and Determination of Potential Sites (2018 to 2028)
(iii) Detailed Site Investigation and In-Situ Tests (2029 to 2038)
(iv) Repository Design and Safety Assessment (2039 to 2044)
(v) Repository Construction (2045 to 2055)

The purpose of the first stage is to assess the feasibility of SNFD in Taiwan, therefore, TPC started to carry out geological, geophysical and geochemical surveys to establish the geological and hydrogeological conceptual modals in Taiwan, and the Preliminary Feasibility Assessment Report for the SNFD Technology in Taiwan (SNFD2009) had been submitted in 2009. In this report, 3 types of potential host rock for SNFD were purposed, which included granites, mudstones (including shale, argillite, and slate), and Mesozoic basement rocks. Moreover, the preliminary conceptual modals of geology and hydrogeology in K area, where is a granitic island in offshore, Western Taiwan (see Fig. 1), were purposed in "The Technical Feasibility Assessment Report on Spent Nuclear Fuel Final Disposal (SNFD2017 Report)". In addition, during the process of developing the report, our faculty can be equipped with sufficient knowledge of engineering and safety assessment techniques for SNFD.

The preliminary geological conceptual model is constructed by integration of surface geological and geophysical investigation and boreholes data, and the preliminary hydrogeological conceptual model is based on the geological, geophysical and geochemical survey in K area. Furthermore, all the parameters from field data and in situ hydraulic test are reorganized as discrete fracture network (DFN) recipes to use in hydrogeological concept.

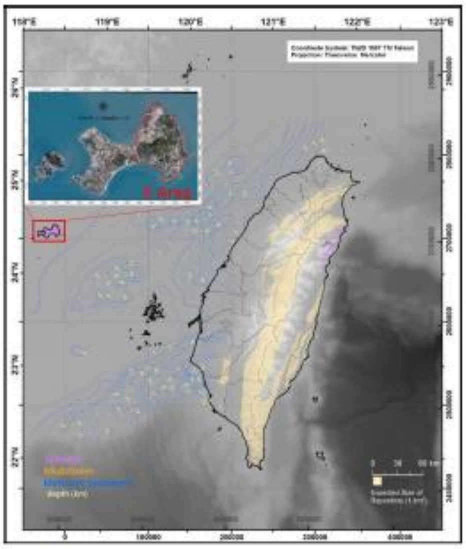


Fig. 1. Location of potential host rocks in Taiwan and K area

2. METHODOLOGY

2.1. *Geological Conceptual Model*

The geological conceptual model was based on geological and geophysical survey field work during 1999 to 2012, in K area. Geological mapping and surface gravity and magnetic (GM) survey were compiled to obtain distribution of structural lineaments. According to resistivity imaging profiles (RIP), identification of major water conducting features (MWCFs) can be differentiated from water-less structures to further understand spatial extension and distribution of MWCFs. Integration of aforementioned data, K area could be divided into 3 geological units: rock units in lithology, MWCFs, and doleritic dykes. The parameters of geological units were described in Table 1.

From 2002 to 2007, 6 cored boreholes (KMBH#) of HQ size with 500 m depth were drilled. These boreholes were used to verify the accuracy of surface geological survey and formed to in situ hydraulic test. The underground fractures were mapping by geophysical logging (borehole camera and full-waveform sonic log).

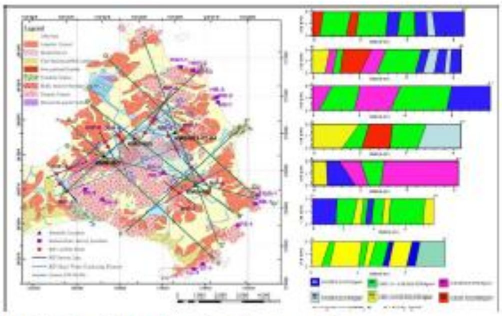


Fig. 2.Geological and geophysical survey of K area

2.2. *Hydrogeological Conceptual Model*

The hydrogeological conceptual model was established by in-situ hydraulic test data. Together with core logging data, 4 hydraulic units were concluded.

(i) Regolith (R0)
The top layer of the regolith is more than 10 m of clay and granite gravels; the underlying layer is granite gneiss fractured by exfoliation joints.

(ii) Intact rock units (R#)
The granite units are mostly intact and often truncated by amphibolite dikes. The granite bedrocks are rarely fractured. The fractures observed are high angle joints that extend to shallow aquifers.

(iii) MWCF (F#)
The cross-hole (KMBH01-02-04) testing indicated that TaiWuShan (TWS) fault (F1) and the related branch fractures (F2) are fractured and highly permeable.

(iv) Flow barrier structure (D#)
The cross-hole (KMBH01-02-04) testing indicated that the northeast oriented doleritic dikes in the K area were the important flow barrier structure. Hence, groundwater flowing towards northwest may not be able to cross this discontinuity. The surface geological survey shows that the frequency of this flow barrier could be reasonably assumed to be 100 m width per 1,000 m spacing.

Table 1. Geological and hydraulic unites

Unite ID	R0	R1	R2	R3	F1	F2	D#
	Regolith	TWS rock mass	TWS rock mass	Transition zone	TWS fault	TWS fault branch	Doleritic dike
Lithology	regolith	Granitic gneiss, Migmatite	Granitic gneiss	Granitic gneiss, Migmatite	Fault zone	Fault zone	Dolerite
Thickness (m)	70	--	--	--	>150	8-15	100m per km
Strike/dip	--	--	--	--	N64E/70N	N80W/50S	N30E/80N
Hydraulic conductivity (m/s)	5×10^{-6} to 1×10^{-4}	4.1×10^{-12} to 1×10^{-9}	4.1×10^{-12} to 1×10^{-9}	4.1×10^{-12} to 1×10^{-9}	3×10^{-8} to 1×10^{-4}	3×10^{-8} to 1×10^{-4}	4.1×10^{-12} to3.6×10^{-11}
Effective Porosity	--	--	--	--	0.01	0.015	--

The configuration of these hydraulic units are shown in the Fig. 3. The results of oxygen and hydrogen stable isotopes indicated the groundwater collected from TWS fault zone were supplied by the infiltration and recharge of meteoric water. The groundwater flows in the northwest direction along fracture zones and changes to the north direction after passing the F1 and doleritic dikes. Thus, groundwater flow in the K area is affected by dikes, F1 and F2 structures, the boundary conditions are factors that affect the groundwater flow.

Some simplifying assumptions in the conceptual model is described below. The geomorphology of the eastern Kinmen is similar to western Kinmen. Base on the observation of thick sedimentary layers at the central of the island, a no-flow boundary condition is assumption for the western side of the K area. Groundwater flow is slower with depth increase. Therefore, a no-flow boundary condition is applied for the model bottom assuming the bottom is at a sufficient depth. The side boundaries, except the western and bottom sides, could be assigned to be Dirichlet boundary conditions For the shallow level, the boundary conditions depend on the outcrop, which means the numerical grids for outcrop could be assumed to be no-flow boundary condition and the rest are assumed to be Dirichlet boundary condition. For the deep level, the northwestern and southeastern boundaries for the K area in the numerical modeling could be assumed to be Dirichlet boundary conditions, assuming the topography of southeastern China does affect groundwater flow in the K area.

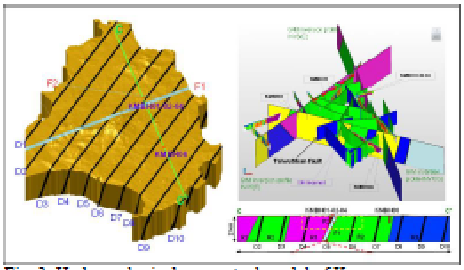


Fig. 3. Hydrogeological conceptual model of K area

2.3. *DFN Recipes*

In SNFD program, 3 types of fractures measurements were used in filed works. Outcrop fractures were measured by scan-line, tunnel fractures were measured by scan-window, and borehole fractures were measured by borehole image. In this study, only borehole fractures were selected to generate the DFN receipts. The fractures from KMBH01 to 04 exhibit similar variation pattern with depth, FDMA and FDMB fracture domains are separated at 70 m depth. The FDMA are classified into 4 clusters, and the FDMB are classified into 5 clusters (see Fig. 4). Fracture size (k_r, La Pointe, 2002)is followed power-law distribution as 2.6; r_0 is intentionally changed from 0.05 m to 0.1 m in order to create larger fractures to generate more connected fractures for demonstration purposes. The limit of fracture size is given by "eq. (1)."

$$P_{32}[r_{min}, r_{max}] = P_{32}[r \geq r_0]\left(\frac{(r_{min})^{(2-k_r)} - (r_{max})^{(2-k_r)}}{(r_0)^{(2-k_r)}}\right) \quad (1)$$

Fracture transmissivity used the empirical equations from Forsmark, Sweden (Vidstrand *et al.*, 2010).

$$T_{FDMA} = 1.51 \times 10^{-7} \times (L^{0.7}) \quad (2)$$

$$T_{FDMB} = 3.98 \times 10^{-10} \times (L^{0.5}) \quad (3)$$

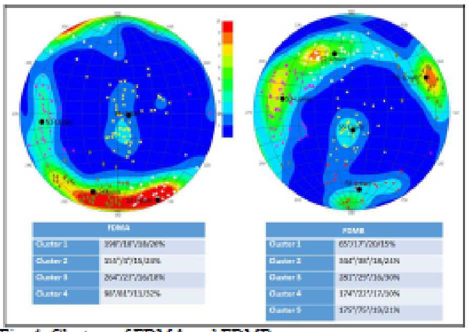


Fig. 4. Clusters of FDMA and FDMB

And the transport aperture is also an empirical equation from Sweden (Follin *et al.*, 2005). All the parameters of DFN recipes shows in Table 2.

$$e = 0.5\sqrt{T} \quad (4)$$

Table 2. DFN recipes of K area

Fracture Domain		FDMA	FDMB
Elevation (m)		-70 to 0	-500 to -70
Fracture clusters (Trend, Plunge, κ, $P_{32,\,rel}$)	Cluster 1	(198, 18, 18, 26%)	(65, 17, 20, 15%)
	Cluster 2	(155, 4, 15, 24%)	(344, 38, 18, 24%)
	Cluster 3	(264, 23, 16, 18%)	(281, 29, 16, 30%)
	Cluster 4	(98, 81, 11, 32%)	(174, 22, 17, 10%)
	Cluster 5	--	(175, 75, 19, 21%)
Fracture intensity		P_{32}=2.4	P_{32}=0.3
Fracture size (m)		k_r=2.6, r_0=0.1 , r_{min}=4.5 , r_{max}=564	
Transport aperture (m)		$e = 0.5\sqrt{T}$	
Fracture Transmissivity (m^2/s)		$1.51 \times 10^{-7} \times (L^{0.7})$	$3.98 \times 10^{-10} \times (L^{0.5})$

3. RESULTS AND DISCUSSION

The groundwater flow modelling is constructed on DarcyTools, a finite volume code developed for the deep rock behaviour in large scale by SKB (Svensson et al. 2010). The following results show the comparison between base case (BC) and variation cases.

Base case (Fig. 5.) is a simplified model of K area, the boundary condition was set as specified head at top and no-flow at lateral. The existing dykes affect the flow paths mainly toward to the northeast direction. Some particles move deeper might been affected by the gradient of TWS. Most of the particles discharge on the land and close to the shoreline, a few of particles were caught by F2 and discharge.

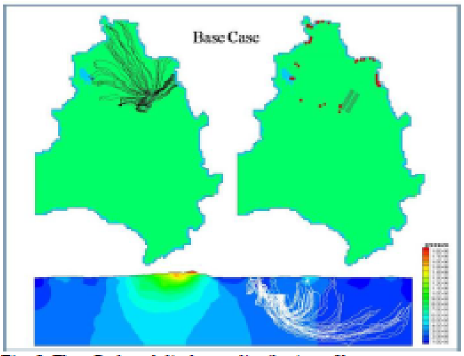


Fig. 5. Flow Path and discharge distribution of base case

According to the practices of Forsmark site, (Follin, 2008) it indicates that both fracture frequency and permeability decrease with depth. This is typically modelled as a continuous change or in steps. To test the sensitivity of flow and transport to a step change, case I (Fig. 6.) is run where the hydraulic conductivity below -700 m is reduced to 1×10^{-12} m/s. It means the bottom of the modelling is a no-flow boundary. It cause the flow path decrease and particles toward deeper layer more difficultly.

Dykes are generally believed to be less permeable than the host rock. In the base case representation, the dykes have a hydraulic conductivity of 1×10^{-11} m/s. Case II (Fig. 7) is run where the conductivity is reduced to 1×10^{-12} m/s. The results indicate dykes form a group of aquiclude. Most flow paths are parallel with dykes, and more particles move deeper. The result of simulation is fairly similar to BC.

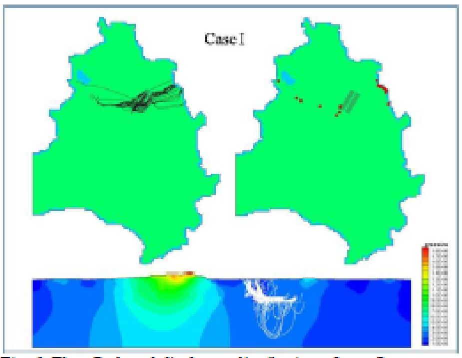


Fig. 6. Flow Path and discharge distribution of case I

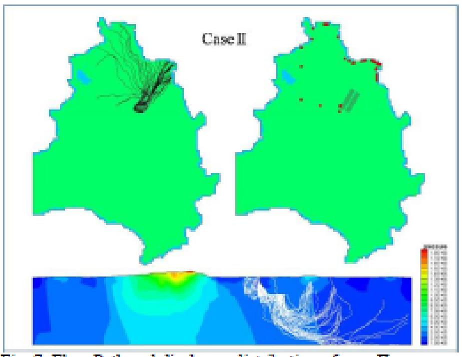


Fig. 7. Flow Path and discharge distribution of case II

K area is geographically close to mainland China, it might be assumed a regional gradient could influence the local flow. In practice, Case III (Fig. 8) is obtained by taking the head on the upstream boundary from BC increased by 80 m (the length of the island in the NNW to SSE direction being approximately 8 km). This results in a gradient of 1% in the NNW-SSE direction. The results show that the flow paths now are not as deep as in BC, and that the pressure field is quite different, too. The local gradient might influence that most flow paths and associated discharge locations now are more concentrated towards the coast, yielding shorter travel paths. Also, the regional gradient does not result in any increase of the equivalent initial flux at repository depth, it might be explained by the fact that the repository is shielded by the combination of the successive dyke zones and the F2 such that the repository zone is protected against the increased gradient.

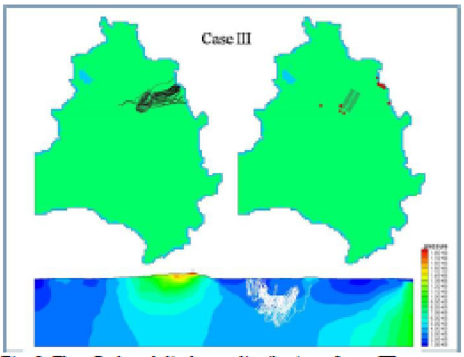


Fig. 8. Flow Path and discharge distribution of case III

The DFN model is inherently uncertain due to its stochastic nature. Thus, running multiple realizations of the DFN and flow simulations is a means to quantify this uncertainty. If a sufficient number of realizations are run, statistical distributions of the performance measures over multiple realizations can be performed. In case IV, only 2 additional realizations (with the same DFN input statistics as BC) are run as an exemplification of the potential uncertainty related to stochastic DFN variability. The fracture realization result of BC shows in the left of Fig. 9. The realization of BC contain more fractures intersecting the deposition tunnels than the others. However, the discharge locations are essentially the same for all realizations, it indicated the topography and geological structures greatly imply a structural control on the flow path geometries. This case shows the influence of flow paths from different realizations, but the realistic degree still needs to be quantified.

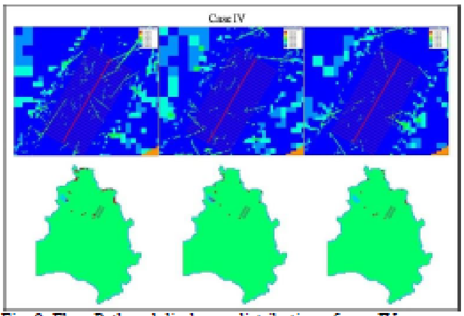


Fig. 9. Flow Path and discharge distribution of case IV

However, the limited of field data and in situ test, the existing conceptual model is a highly simplified representation of reality. The performance measures calculated are also likely optimistic. Next stage, for the geological characterization survey of the potential sites hosting particular geological disposal facilities, in-situ surveys and data analyses, covering installation of borehole seismometers and analysis of data obtained this way, borehole in-situ stress measurement and analysis, large-scale pumping test and high density borehole hydraulic test, are required to be undertaken. Surveys with higher accuracy requirements are to be performed to obtain detailed data to enable the building of the deep geological concept model for use in performance/safety assessments and analyses.

4. CONCLUSION

In the first stage of SNFD Plan, "Investigation and Evaluation of the Potential Host Rock", the main mission is to focus on the study of feasibility of geological disposal in Taiwan without any siting procedure involved.

In order to appropriately develop the investigation and assessment techniques used for deep geological characterization, the results of all geological and geophysical surveys are periodically reviewed to make sure that our research work successfully meet the requirements of each stage.

Discrete Fracture Network and up-scaled Equivalent Continuum Porous Medium groundwater flow modelling using code DarcyTools have been performed for the K-area. The study is beneficial for further development of both performance and safety assessment.

The Simplified base case has been propagated to additional variant simulations, such as hydrogeological properties uncertainty, multiple realizations and regional gradient. The local scale flow paths are mainly controlled by geological units, such as host rock properties, dykes and geological structures. And the regional gradient affects most flow paths and associated discharge locations. The variant cases demonstrate that the topography and geological structures greatly affect the flow path geometries.

Currently, the geological and hydrogeological conceptual models are highly simplified. It's necessary to acquire detailed parameters for further development of performance and safety assessment.

ACKNOWLEDGEMENTS

Thanks for the experts from SKB International AB providing lots of professional advice and experience, Industrial Technology Research Institute (ITRI) assisting the geological and geophysical investigation field work, and Institute of Nuclear Energy Research (INER) assisting the associated experiment in Labs. The "*SNFD2017 Report*" would not been accomplished without the contributions of SNFD team.

REFERENCES

1. Follin, S., Stigsson, M. and Svensson, U., 2005, Regional hydrogeological simulations for Forsmark - numerical modelling using DarcyTools Preliminary site description Forsmark area – version 1.2, *Report R-05-60*. Svensk Kärnbränslehantering AB (SKB).

2. Follin, S. (2008), Bedrock hydrogeology Forsmark, Site descriptive modelling, SDM-Site Forsmark, *SKB, R-08-95*. Svensk Kärnbränslehantering AB (SKB).

3. La Pointe, P.R. 2002, Derivation of parent fracture population statistics from trace length measurements of fractal fracture populations, *Int. J. Rock Mech. Min. Sci.*, 39: 381-388.

4. TPC, 2006 (revise in 2010 &2014), *Spent Nuclear Fuel Final Disposal Plan (in Chinese)*, Taiwan Power Company.

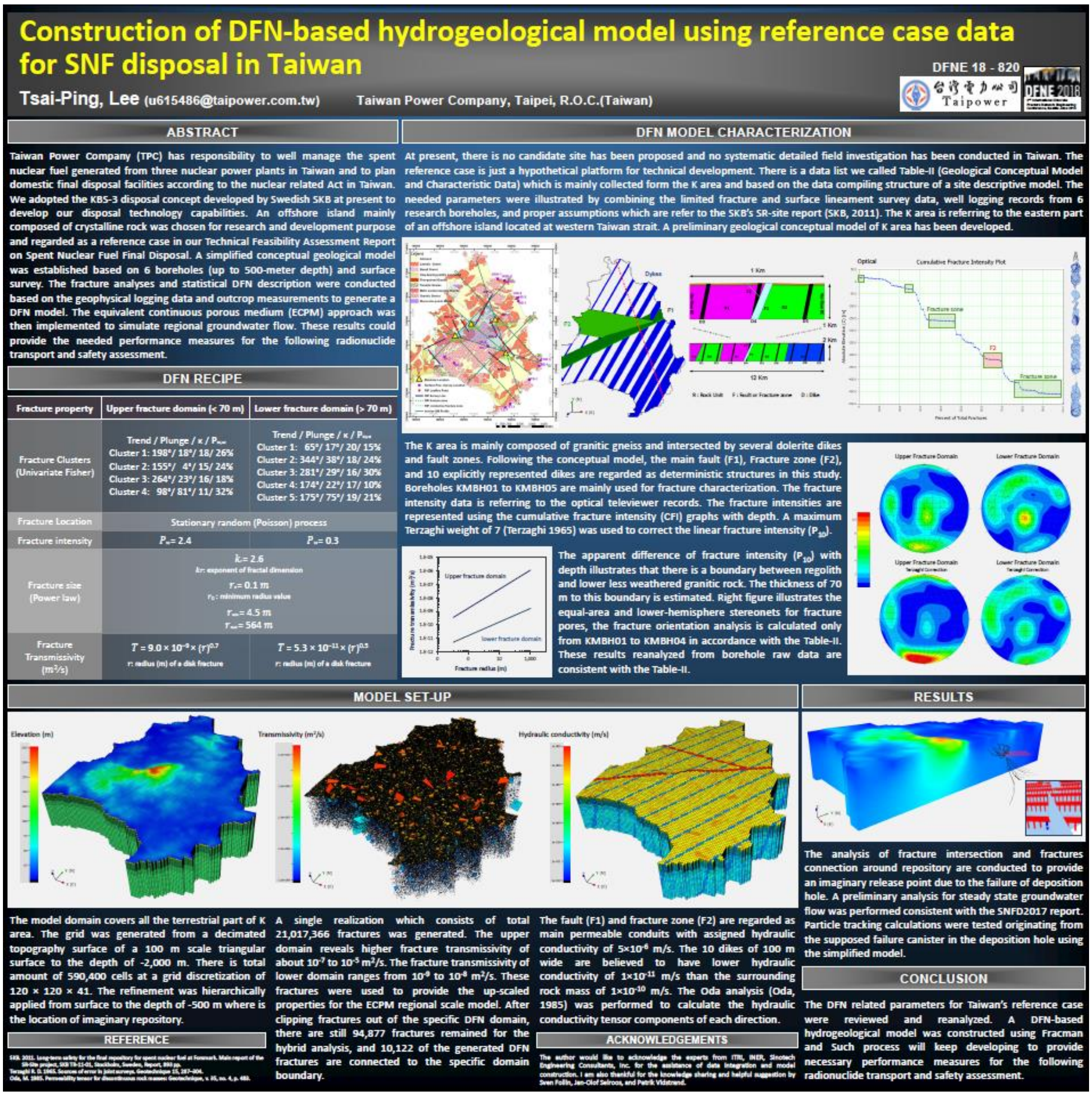
5. TPC, 2009, Preliminary *Feasibility Assessment Report for the Spent Nuclear Fuel Final Disposal Technology in Taiwan (in Chinese)*, Taiwan Power Company.

6. Svensson U, Ferry M, Kuylenstierna H-O, 2010, DarcyTools version 3.4 - Concepts, Methods and Equations, *Report R-07-38*,Svensk Kärnbränslehantering AB (SKB).

7. Vidstrand, P., Follin, S., Zugec, N. 2010, Groundwater flow modelling of periods with periglacial and glacial climate conditions – Forsmark, *Report R-09-21*. Svensk Kärnbränslehantering AB (SKB).

附錄 IV. 發表海報

發表海報 I



DFNE 18 - 919

2nd International Discrete Fracture Network Engineering Conference, Seattle June 2018

52nd US Rock Mechanics/ Geomechanics Symposium 2018 Seattle, Washington, USA

The applications of discrete fracture network model for spent nuclear fuel final disposal program in Taiwan

Tsung-Hsiang Chiu (u271130@taipower.com.tw)
Department of Nuclear Back-end Management, Taiwan Power Company,
No.242, Sec. 3, Roosevelt Rd.,Taipei, Taiwan, R.O.C.

Taipower 台灣電力公司

ABSTRACT :

As the owner and operator of all nuclear power plants in Taiwan, Taiwan Power Company (TPC) is responsible for the management of high level radioactive waste. According to the R&D results of TPC, "The Technical Feasibility Assessment Report on Spent Nuclear Fuel Final Disposal (SNFD2017 Report)" has been accomplished to make sure that the geological condition of Taiwan is suitable for geological disposal. The geological conceptual model developed in SNFD2017 Report is based on the geological, geophysical and geochemical surveys conducted on K area, which is a granitic offshore island. The hydrogeological conceptual model is constructed according the boreholes logging data and geophysical investigations of K area. Furthermore, all information derived from field data and in-situ hydraulic tests are reorganized as needed by DFN recipes. In the preliminary stage, TPC has been required to develop various underground assessment techniques which will be used under fractured crystalline rock environment. Basing on this SDM, a preliminary safety assessment and safety case have been accomplished. All the results have been integrated to "Taiwan reference case" in SNFD2017 Report.

INTROCTUCTION

In 1979, the first nuclear power plant (NPP) was launched in Taiwan. In 2017, 6 reactors are still in service in 3 NPPs. Being the owner and operator of all NPPs in Taiwan, Taiwan Power Company (TPC) has been requested by the government to be responsible for both the management and disposal of radioactive waste. The R&D programs (Research and Develop programs) for the spent nuclear fuel disposal were executed in 1986, and the "Spent Nuclear Fuel Final Disposal (SNFD) Plan was submitted in 2004. The schedule of the SNFD can be divided into 5 stages as following:

- Investigation and Evaluation of the Potential Host Rock (2005 to 2017)
- Selection and Determination of Potential Sites (2018 to 2028)
- Detailed Site Investigation and In-Situ Tests (2029 to 2038)
- Repository Design and Safety Assessment (2039 to 2044)
- Repository Construction (2045 to 2055)

TPC started to carry out geological, geophysical and geochemical surveys to establish the geological and hydrogeological conceptual modals in Taiwan. Moreover, the preliminary conceptual modals of geology and hydrogeology in K area, where is a granitic island in offshore, Western Taiwan (see Fig. 1), were purposed in SNFD2017 Report.

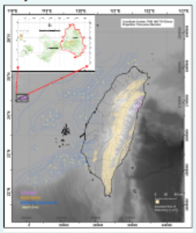


Fig.1 The distributions of Potential host rock in Taiwan

METHODOLOGY

Geological Conceptual Model

The geological conceptual model was based on geological and geophysical survey field work during 1999 to 2012, in K area. The geological units are divided into lithology, major water conducting features(MWCFs) and doleritic dykes. The lithology are defined as gravity and magnetic (GM) survey data; the MWCFs are defined as resistivity imaging profiles(RIP.); and the dykes are mapped by in-situ field survey. The distribution of geological units shows in Fig. 2 and the parameters are described in Table 1.

Hydrogeological Conceptual Model

The configuration of these hydraulic units are shown in the Fig. 3. The groundwater of TWS fault zone were mainly supplied by the infiltration and recharge of meteoric water. The direction of groundwater flow in K area is changed to north from northwest by dikes, F1 and F2 structures.

We assumed the western side of the K area a no-flow boundary condition, base on the observation of thick sedimentary layers at the central Kinmen island. Groundwater flow is slower with depth increase. Therefore, a no-flow boundary condition is applied for the model bottom assuming the bottom is at a sufficient depth. Other boundary is assumed as Dirichlet boundary condition.

DFN Recipes

In SNFD program, 3 types of fractures measurements were used in filed works. Outcrop fractures were measured by scan-line, tunnel fractures were measured by scan-window, and borehole fractures were measured by borehole image. In this study, the DFN recipes are set up by 4 boreholes. The fracture domains are divided into FDMA and FDMB by cumulative fracture intensity. In the DFN recipes, the center location of fracture is generated by poissonian process, and the fracture size distribution(k_r) is followed the power-law distribution. Fracture transmissivity and transport aperture use the empirical equations from Forsmark, Sweden. The DFN recipes are showed in Fig. 4 and Table 2.

Table 2 : DFN recipes of K area

Fracture Domain		FDMA	FDMB
Elevation (m)		-70 to 0	-500 to -70
Fracture clusters (Trend, Plunge, κ, $P_{32,rel}$)	Cluster 1	(198, 18, 18, 26%)	(65, 17, 20, 15%)
	Cluster 2	(155, 4, 15, 24%)	(344, 38, 18, 24%)
	Cluster 3	(264, 23, 16, 18%)	(281, 29, 16, 30%)
	Cluster 4	(98, 81, 11, 32%)	(174, 22, 17, 10%)
	Cluster 5	–	(175, 75, 19, 21%)
Fracture intensity		$P_{32}=2.4$	$P_{32}=0.3$
Fracture size (m)		k_r=2.6, r_0=0.1, r_{min}=4.5, r_{max}=564	
Transport aperture (m)		$e = 0.5\sqrt{T}$	
Fracture Transmissivity (m²/s)		$1.51\times10^{-7}\times(L^{0.7})$	$3.98\times10^{-10}\times(L^{1.2})$

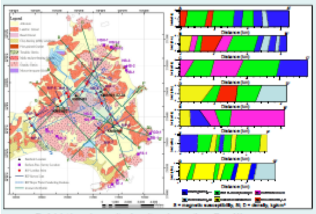


Fig.2 Joint inversion results of gravity and magnetic profiles of K area

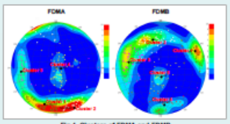


Fig.4 Clusters of FDMA and FDMB

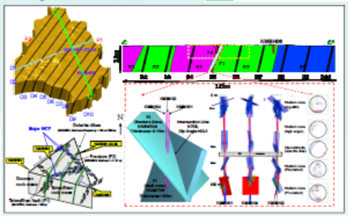


Table 1 : Geological and hydraulic unites

Units ID	R0	R1	R2	R3	F1	F2	D#
	Regolith	TWS rock mass	TWS rock mass	Transition zone	TWS fault	TWS fault branch	Doleritic dike
Lithology	regolith	Granitic gneiss, Migmatite	Granitic gneiss	Granitic gneiss, Migmatite	Fault zone	Fault zone	Dolerite
Thickness (m)	70	–	–	–	>150	8-15	100 m per km
Strike/dip	–	–	–	–	N64E/70N	N80W/50S	N30E/80N
hydraulic conductivity(m/s)	1×10^{-5}	1×10^{-10}	1×10^{-10}	1×10^{-10}	5×10^{-6}	5×10^{-6}	1×10^{-11}
Effective Porosity	–	–	–	–	0.01	0.015	–

RESULTS AND DISCUSSION

The groundwater flow modeling was constructed on DarcyTools, a finite volume code developed for the deep rock behaviour in large scale by SKB. The following results show the comparison of base case (BC) and variation cases.

Base case is a simplified model of K area, the boundary condition was set as specified head at top and no-flow at lateral. The existing dykes affect the flow paths mainly toward to the northeast direction. Some particles move deeper might been affected by the gradient of TWS. Most of the particles discharge on the land and close to the shoreline, a few of particles were caught by F2 and discharge. Otherwise, there are 3 various cases for testing the sensitivity of hydraulic conductivity, aquiclude and regional gradient. The results and scenarios shows in Fig.5 and table 3.

In case I, the hydraulic conductivity below -700 m is lower to 1×10^{-12} (m/s). This change makes all values uniform. In particular, there are no longer any high values of hydraulic conductivity present. The step decrease in hydraulic conductivity will likely result in less deep flow paths since the rock interface where the change occurs will act like a no-flow boundary. it is seen that the flow paths are less deep due to the reduced hydraulic conductivity. This has essentially the same effect as a salinity interface.

In case II, the hydraulic conductivity in dykes is lowered by one order of magnitude to 1×10^{-12} (m/s). The result shows similar trend with BC. It means the conductivity of aquiclude might not be sensitivity in the conceptual model.

In case III, the increasing gradient of groundwater head from NNW direction influence the flow paths and discharge locations. It indicates that the repository might be shield by the combination of the successive dyke zones and the F2 such that the repository zone is protected against the increased gradient.

CONCLUSION

As the first stage of SNFD Plan, "Investigation and Evaluation of the Potential Host Rock", the main missions focus on feasibility of geological disposal in Taiwan. There is no any sitting procedure in this stage. All the geological and geophysical survey are conformed to the stepwise requirement, to develop the investigation and assessment techniques of deep geological characterization.

Discrete Fracture Network and up-scaled Equivalent Continuum Porous Medium groundwater flow modelling using code DarcyTools has been performed of the K-area. The study could assist to produce a number of performance measure for application of performance and safety assessment.

The Simplified base case has been propagated to additional variant simulations, such as hydrogeological properties uncertainty, multiple realizations and regional gradient. The local scale flow paths mainly controlled by geological units, such as host rock properties, dykes and geological structures. And the regional gradient affects most flow paths and associated discharge locations. The variant cases shows the topography and geological structures greatly affect the flow path geometries.

Currently, the geological and hydrogeological conceptual models are highly simplified. It's necessary to obtain detailed parameters for further work in performance and safety assessment.

Table 3 : Assumption of base case and variant cases

CASES	Base assumption	Variant case
Base Case	1. specified head at the top boundary and no-flow boundary at lateral 2. the salinity of sea water is set equal to 3.2% 3. density-driven flow 4. temperature is a constant	
Case I		the hydraulic conductivity below -700 m is reduced to 1×10^{-12} m/s
Case II		the hydraulic conductivity of dykes is reduced to 1×10^{-12} m/s
Case III		the regional gradient of approximately 1% in the NNW-SSE direction (from Fu-Chien, China)

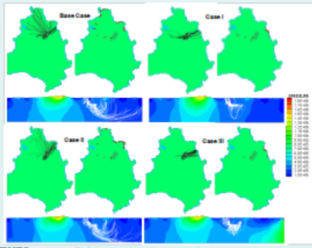


Fig.5 the comparison of base case and variant cases

ACKNOWLEDGEMENTS

Thanks for the experts from SKBI AB providing lots of professional advice and experience, Industrial Technology Research Institute (ITRI) assisting the geological and geophysical investigation field work, and Institute of Nuclear Energy Research (INER) assisting the associated experiment in Labs. The "SNFD2017 Report" would not been accomplished without the contributions of SNFD team.

REFERENCES

1. Follin, S., Stigsson, M. and Svensson, U., 2005, Regional hydrogeological simulations for Forsmark - numerical modelling using DarcyTools Preliminary site description Forsmark area – version 1.2, Report R-05-60. Svensk Kärnbränslehantering AB (SKB).
2. Follin, S. (2008), Bedrock hydrogeology Forsmark, Site descriptive modelling, SDM-Site Forsmark, SKB, R-08-95. Svensk Kärnbränslehantering AB (SKB).
3. La Pointe, P.R. 2002, Derivation of parent fracture population statistics from trace length measurements of fractal fracture populations, Int. J. Rock Mech. Min. Sci., 39: 381-388.
4. TPC, 2006 (revise in 2010 &2014), Spent Nuclear Fuel Final Disposal Plan (in Chinese), Taiwan Power Company.
5. TPC, 2009, Preliminary Feasibility Assessment Report for the Spent Nuclear Fuel Final Disposal Technology in Taiwan (in Chinese), Taiwan Power Company.
6. Svensson U, Ferry M, Kuylenstierna H-O, 2010, DarcyTools version 3.4 - Concepts, Methods and Equations, Report R-07-38,Svensk Kärnbränslehantering AB (SKB).
7. Vidstrand, P., Follin, S., Zugec, N. 2010, Groundwater flow modelling of periods with periglacial and glacial climate conditions – Forsmark,